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SIGNIFICANCE OF ABBREVIATIONS MOST FREQUENTLY ENCOUNTERED IN SOVIET PHYSICS PERIODICALS

AN SSSR	*Academy of Sciences, USSR*
FIAN	*Physics Institute, Academy of Sciences USSR*
GITI	*State Scientific and Technical Press*
GITTL	*State Press for Technical and Theoretical Literature*
GOI	*State Optical Institute*
GONTI	*State United Scientific and Technical Press*
Gosenergoizdat	*State Power Press*
Gosfizkhimizdat	*State Physical Chemistry Press*
Gozkhimizdat	*State Chemistry Press*
GOST	*All-Union State Standard*
Goztekhizdat	*State Technical Press*
GTTI	*State Technical and Theoretical Press*
GUPIAE	*State Office for Utilization of Atomic Energy*
IF KhI	*Institute of Physical Chemistry Research*
IFP	*Institute of Physical Problems*
IL	*Foreign Literature Press*
IPF	*Institute of Applied Physics*
IPM	*Institute of Applied Mathematics*
IREA	*Institute of Chemical Reagents*
ISN (Izd. Sov. Nauk)	*Soviet Science Press*
I YaP	*Institute of Nuclear Studies*
Izd	*Press (publishing house)*
KISO	*Solar Research Commission*
LETI	*Leningrad Electrotechnical Institute*
LFTI	*Leningrad Institute of Physics and Technology*
LIM	*Leningrad Institute of Metals*
LITMiO	*Leningrad Institute of Precision Instruments and Optics*
Mashgiz	*State Scientific-Technical Press for Machine Construction Literature*
MATI	*Moscow Aviation Technology Institute*
MGU	*Moscow State University*
Metallurgizdat	*Metallurgy Press*
MOPI	*Moscow Regional Institute of Physics*
NIAFIZ	*Scientific Research Association for Physics*
NIFI	*Scientific Research Institute of Physics*
NIIMM	*Scientific Research Institute of Mathematics and Mechanics*
NII ZVUKSZAPIOI	*Scientific Research Institute of Sound Recording*
NIKFI	*Scientific Institute of Motion Picture Photography*
OIYaI	*Joint Institute of Nuclear Studies*
ONTI	*United Scientific and Technical Press*
OTI	*Division of Technical Information*
OTN	*Division of Technical Science*
RIAN	*Radium Institute, Academy of Sciences of the USSR*
SPB	*All-Union Special Planning Office*
Stroiizdat	*Construction Press*
URALFTI	*Ural Institute of Physics and Technology*

NOTE: Abbreviations not on this list and not explained in the translation have been transliterated, no further information about their significance being available to us.—*Publisher.*

AN ELECTROMAGNETIC APPARATUS WITH A HIGH RESOLVING POWER FOR THE SEPARATION OF THE ISOTOPES OF THE HEAVY ELEMENTS

L. A. Artsimovich, G. Ia. Shchepkin, V. V. Zhukov, B. N. Makov, S. P. Maksimov, A. F. Malov, A. A. Nikulichev, B. V. Panin, and B. G. Brezhnev

The operating principles and the main features of an electromagnetic apparatus which has been designed and constructed for the separation of isotopes with a relative mass difference of about 1/240 are here described.

An axially-symmetric magnetic field is used (focussing angle 225°) in which the dispersion is proportional to the square of the focussing angle. The dispersion obtained with the separation apparatus is 20 mm for a 1% relative difference in mass. The magnetic field of the apparatus is stabilized to within 0.005% with the help of a circuit containing electron-beam regulators. Ion sources, with a discharge in the vapor of the working and auxiliary substances, were developed for the separation of large and small quantities of the raw material. General-purpose ion collectors were also developed.

Some results of the separation of lead, uranium and plutonium isotopes are given. The enrichment factor in the separation of lead isotopes reaches 300, while for uranium and plutonium it is ~1000.

Description of the Apparatus

To obtain sufficiently pure isotopes with a relative mass difference of about 1/240, a fairly high dispersion, resolving power and accuracy of the stability of the magnetic and electric fields were required. It was also necessary to have conditions for the separation and collection of element isotopes from samples of the raw materials of various amounts: from tens of grams to milligrams – without complicating in any way the transition from one case to another. Finally, the apparatus must be capable of being used for the separation of highly toxic and α-active elements.

In the design of the apparatus, these basic requirements were taken into account.

The magnetic field and the magnetic system. A stationary axially-symmetric focussing field was used whose radial distribution in cylindrical coordinates, in the plane Z = 0, has the form

$$\frac{H(r,0)}{H_0(r_0,0)} = 1 + \left[\left(\frac{\pi}{\psi}\right)^2 - 1\right]\eta + \left[1 - \frac{7}{4}\left(\frac{\pi}{\psi}\right)^2\right]\eta^2 + \left[\frac{19}{8}\left(\frac{\pi}{\psi}\right)^2 - \frac{1}{2}\left(\frac{\pi}{\psi}\right)^4 - 1\right]\eta^3 + \left[\frac{1}{4} - \frac{73}{64}\left(\frac{\pi}{\psi}\right)^2 + \frac{135}{64}\left(\frac{\pi}{\psi}\right)^4\right]\eta^4 + \ldots, \quad (1)$$

where H_0 is the field at the circumference of radius r_0; $\underline{r}$ is the radial coordinate; ψ is the focussing angle, i. e., the value of the azimuth φ at which the rays, leaving the source AB (Fig. 1), are brought to a focus; $\eta = (r - r_0)/r_0$.

In such a field the dispersion is proportional to the square of the focussing angle:

$$\Delta r = r_0 \frac{\Delta m}{m} \left(\frac{\psi}{\pi} \right)^2, \tag{2}$$

as a result of which for comparatively small values of r_0 a sufficient dispersion can be obtained.

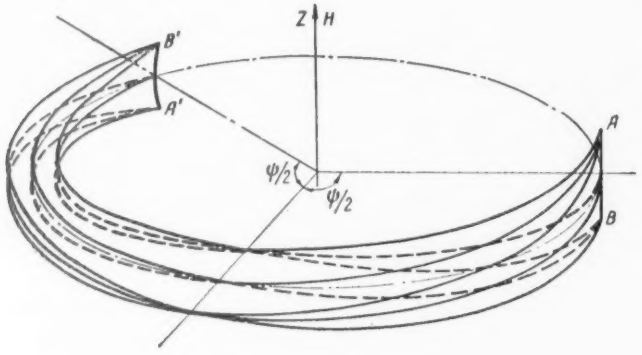

Fig. 1. Ray paths in the magnetic field.

Of course, the actual ion-emitting slit of the ion source has a limiting length $2z_0$ and, consequently, goes out of the plane Z = 0. Therefore, it was necessary to evaluate the possible increase of the aberration for ion rays passing outside the plane Z = 0. Calculation showed that the width of the mass line at the focus is increased with increasing distance from the Z = 0 plane, but in the interval $Z_0 = \pm 50$ mm it does not exceed the allowed value. It was found that the mass line is slightly bent into a parabola with the convexity pointing in the direction of large $\underline{r}$.

As a starting value for the determination of the main features of the focussing system a dispersion of $\Delta r = 20$ mm per 1% $\Delta m/m$ was taken. On the basis of results from prior experiments on the collection of isotopes in ion collectors of other electromagnetic separating equipment, this value for the dispersion could be considered satisfactory for the obtainment of the necessary quality of separation.

The focussing angle is taken equal to 225°, instead of the optimum value $\pi\sqrt{2}$, because of considerations associated with the peculiarities of some of the applications of the equipment.

Using these values, from Eq. (2) the value of the radius of the ion "null trajectory" ρ_0, coinciding with the radius r_0 of the circumference on which $H = H_0$, could be calculated. The value $\rho_0 \approx 1300$ mm was obtained. Taking the normally used value of the accelerating potential difference $V = 3.5 \cdot 10^4$ v and using the well-known relation $H\rho = 144.5\ (MV)^{1/2}$, H_0 could be determined for an ion with an atomic weight M = 240. The rounded-off value of H_0 was found to be 3500 oersteds. Further, the radial distribution of the field, whose appearance is shown in Fig. 2 (theoretical curve), was calculated from Eq. (1).

From consideration of construction, because of the placement of the ion source, the width of the magnetic gap was taken equal to 300 mm. The axial symmetry of the focussing field also determined the construction of the electromagnet (Fig. 3). The total weight of the electromagnet was 30 tons, the weight of copper 4.3 tons. To increase the winding coefficient to 90% and, consequently, to decrease the total weight a low-voltage (voltage of about 4 v) was used with a power supply of ~ 7 kva.

The magnetic circuit of the electromagnet, constructed from 20 steel, has five main parts: a cylinder core, two shoe pieces in the form of truncated cones which have a flat section on one side, and two pole pieces in the form of thick incomplete rings, having an angular span of 240°.

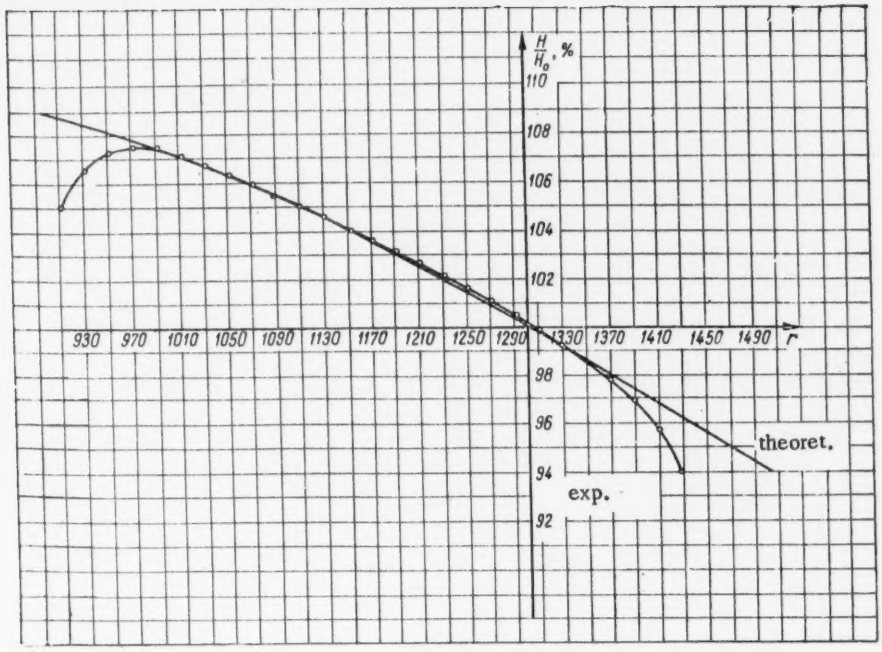

Fig. 2. The radial distribution of the magnetic field strength in the plane Z = 0.

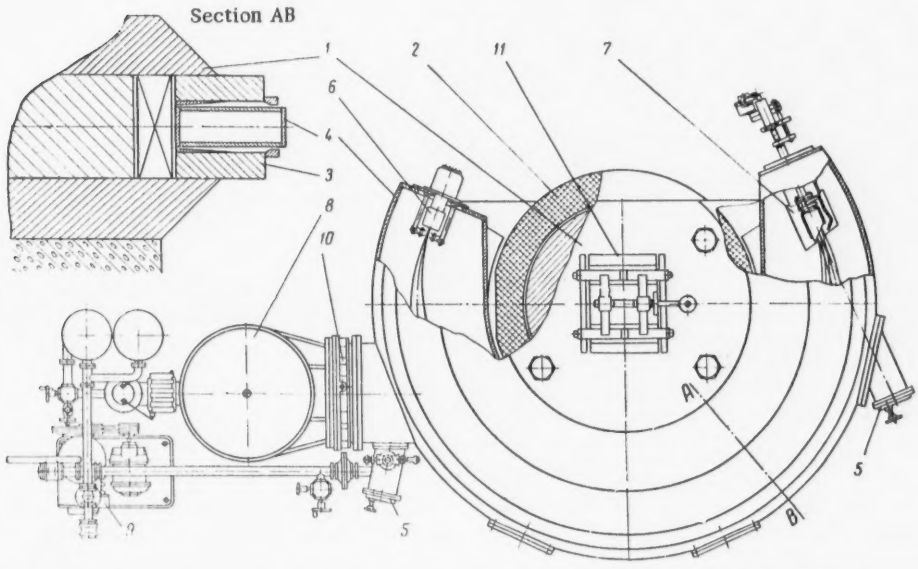

Fig. 3. The electromagnetic and the vacuum system of the apparatus. 1) Pole shoe; 2) winding; 3) pole piece with facing; 4) vacuum chamber; 5) observation windows; 6) ion source; 7) ion collector; 8, 9) vacuum unit; 10) vacuum seal; 11) regulator of the magnetic-field-stabilizing system.

To obtain the focussing field, given by Eq. (1), the poles were covered with an axially-symmetric facing of 20 steel, whose profile was determined by the method of successive approximations. In this way, in the plane Z = 0 the radial distribution of the field was obtained shown in Fig. 2, by the experimental curve. It can be seen that in the interval r_1 = 970 mm to r_2 = 1370 mm there is a sufficiently close agreement between the theoretical and experimental curves. The departure of the actual distribution of the field from the theoretical did not exceed ±0.05%. Further, this width of the working region was sufficient to obtain an ion beam with an angle of divergence in the horizontal plane of 15°.

Power supplies. In the system with the parameters considered, the fluctuations of the working value of the magnetic field were not to exceed 0.005%, while the fluctuations of the accelerating potential 0.01%. To obtain the required constancy of the magnetic field it was not practicable, because of the low winding resistance, to use any of the known methods for stabilizing the current feeding the electromagnet.

A special stabilizing system was developed which used as the regulator an electron-beam oscilloscope-type tube placed in the field of the main electromagnet and compensated by a field of opposite sign from permanent magnets. With the smallest change of the field in the working gap, and consequently of the dispersing field, the

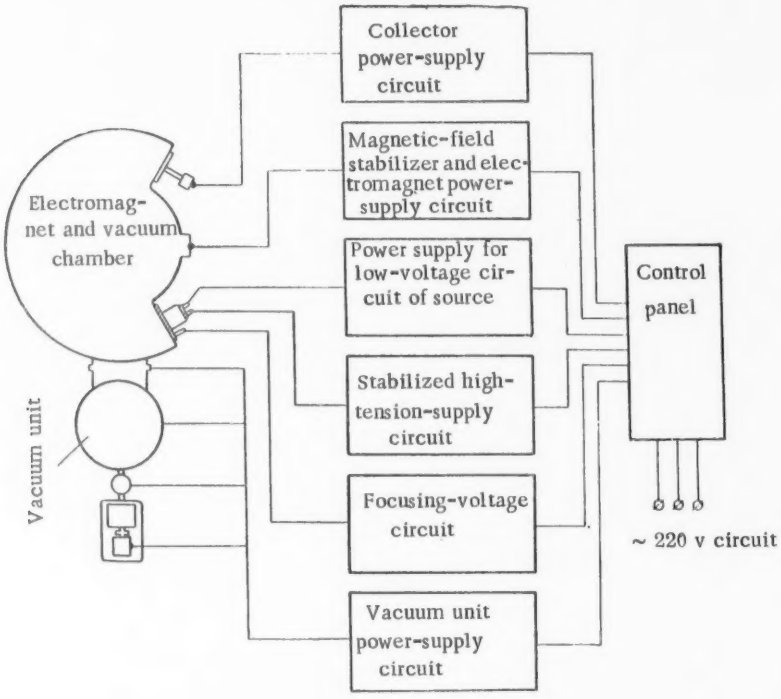

Fig. 4. Block diagram of the apparatus.

electron beam in the tube is deflected to one or the other side of the neutral position, depending on the sign of the change of the main field. This deflection operated a regulating system, which altered in the required way the current in the electromagnet winding, and restored the set value of the field in the working gap. The magnitude of the field in the gap could be controlled over a wide range by a smooth variation of the compensating field by means of a variable magnet used in addition to the permanent magnets. The control signal, produced by the intensity-modulated electron beam, was taken from two metal plates on the outer surface of the tube screen which have a capacitive coupling with the inner surface of the screen bombarded by electrons.

The part of the system supplying power to the electromagnet consisted of a low-voltage selenium rectifier in a six-phase rectification circuit.

The required stability of the field and its adjustment in the necessary range was achieved with the help of the electromagnet power supply and the stabilization system considered.

The power supply for the ion source consisted of a stabilized rectifier giving a voltage of up to 40 kv, stabilized to an accuracy of 0.01%, and a number of unstabilized rectifiers for feeding the focussing, heater, preheating cathode and source gas-discharge circuits, as well as rectifiers for supplying the mechanisms which move and shut the collector. Each of these rectifiers could be adjusted to give a smooth variation of the voltages in the required range. The stabilization of the high tension was achieved by means of a two-stage stabilization system. The regulating elements of the first stage were DN-10-type chokes connected into the primary

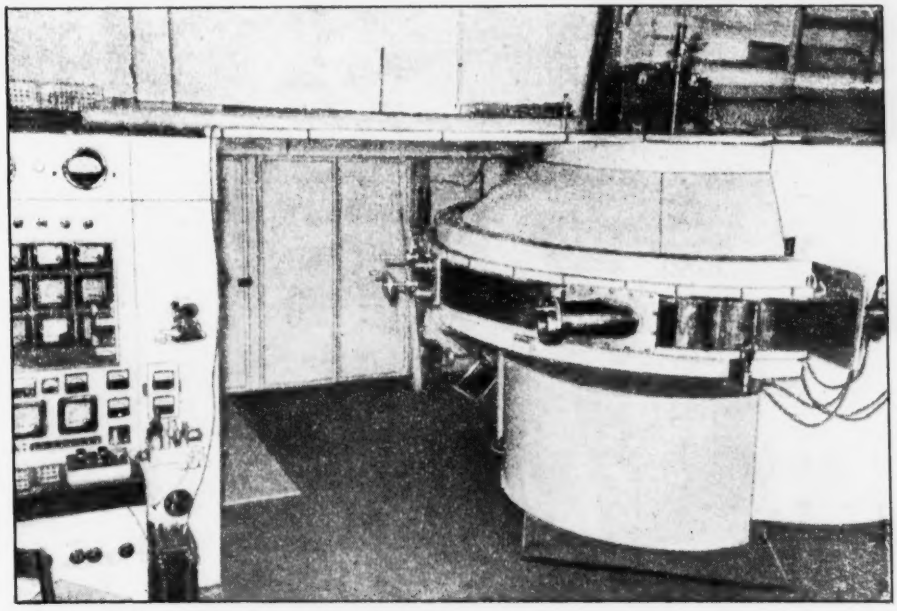

Fig. 5. General view of apparatus.

circuit of the step-up transformer. In the second stage the regulating elements used were G-65/300 valves connected in series with the load. The power-supply system also contained a circuit for stabilizing the current for the discharge in the source. The circuit consisted of a valve rectifier whose voltage output, being the accelerating potential for the electrons heating the cathode, changed with the required phase with changes of the discharge current. The control voltage was taken from a resistance connected in series with the discharge gap [1]. The block diagram of the power-supply system of the apparatus is shown in Fig. 4.

The vacuum system. The vacuum system of the apparatus consisted of a C-shaped vacuum chamber, made from nonmagnetic stainless steel EIa -1T, evacuated by a vacuum unit VU-5-7 (see Fig. 3), and an assembly for changing the ion sources and collectors when working with toxic substances. The shape and size of the vacuum chamber were determined by the shape and dimensions of the ion beam. The vacuum unit, having a pumping speed of about 3000 liters/sec in the region of pressure of 10^{-4}-10^{-5} mm Hg, enabled working pressures of $4\text{-}6 \cdot 10^{-6}$ mm Hg to be obtained under all the working conditions of the apparatus.

The device for changing the sources and collectors in work with toxic substances consisted of a system of air locks made from rubberized material, pipes, ventilators and aerosol filters. With the help of this system, the chamber could be filled with dry air from a special drier, the sources and collectors could be changed without contact of the inner volume of the chamber with the outside air and the preliminary pumping out of the vacuum chamber could be performed. After preliminary evacuation to a pressure of 10^{-1}-10^{-2} mm Hg, the chamber was connected to the operating vacuum unit through a valve of large area (200×600 mm^2) for further evacuation. In this way when working with toxic substances any contact of the personnel with these substances, or their products, was excluded.

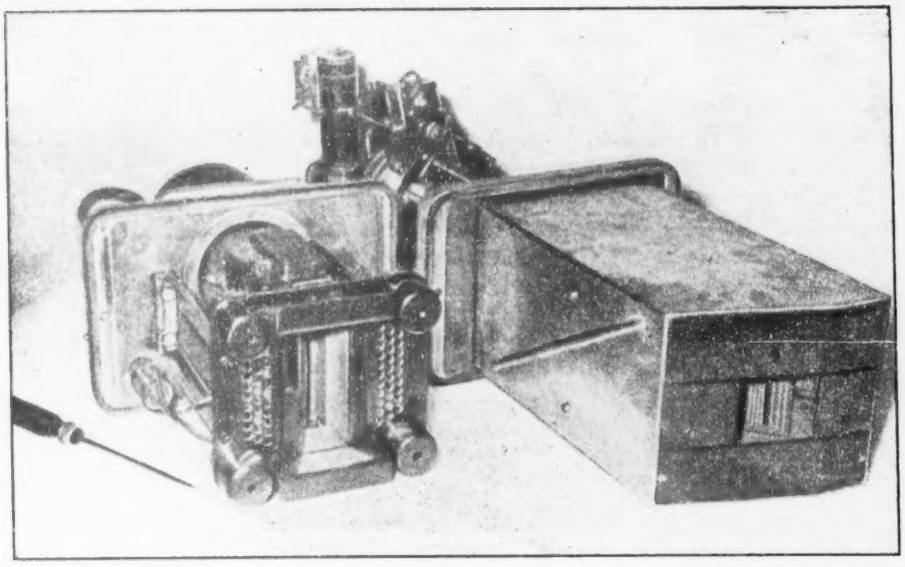

Fig. 6. External view of the ion source and collector.

In Fig. 5 the exterior view of the apparatus is shown.

Ion sources and collectors. A beam of positive ions of the element being separated was produced by an ion source, in the magnetic field, by an arc discharge in the vapor of the working substance.

It was necessary to separate isotopes not only from large quantities of the raw mixture (tens of grams), but also from small quantities (milligrams). Therefore, a source was developed having two independent ovens and heaters for vaporizing the working substance, with a common gas-discharge tube. One of the ovens was loaded with large, and the other with small quantities of the substance. When small quantities of the raw mixture were used it was possible to adjust the system using ions of the auxiliary element, whose atomic weight was close to that of the main element, placed in the big oven. Only after the required operating conditions of the apparatus were attained was the heater of the small oven switched on and in this way the separation of isotopes using very small quantities of the raw mixture was achieved by the arc discharge in the ion source. With this method unproductive losses of the working substance during the adjustment of the system were excluded. The construction of the source enabled the process of isotope separation to be carried out at oven temperatures of up to 1000°C. Figure 6 shows the external view of the source.

For collecting the isotopes separated from a beam of singly-charged ions a collector was developed whose external appearance is shown in Fig. 6, at the right. A water-cooled copper block, with several chambers for the collection of isotopes, is situated in a copper case which has a graphite entry diaphragm. The entry slits of the collecting chambers were covered by graphite shutters during the adjustment of the apparatus to prevent contamination. The distance between the entry slits of the neighboring chambers was determined by the dispersion for a given relative mass difference of the isotopes to be separated. In particular, for $\Delta m/m = 1/240$ the dispersion was about 8.5 mm. The collecting chambers were made from materials which, in each case, were the most suitable for the subsequent chemical processing; copper and graphite were frequently used. To check on the quality of the focussing, electron indicators were used in the collectors. The principle of their operation is based on the use of secondary electron emission from the graphite surface due to the ion bombardment. The secondary electrons, which were knocked out of a graphite target placed in the plane of the front wall of the collector and inclined relative to the direction of the magnetic field, after moving along the lines of force of the field reached a narrow entry slit of an electron collector situated in the upper part of the ion collector. By shifting the ion beam in a radial direction with a small frequency (about 10 c/sec) and synchronizing with it the time base of an oscillograph, it was possible with the help of the oscillograph to measure the electron current at the collector and to observe the curves of the distribution of current density in the ion beam, i. e., the

mass spectrum. When the quality of the focussing reached the necessary level, the modulation of the ion beam was stopped and its operating position was set and maintained with the help of the electron indicators.

EXPERIMENTAL RESULTS

Lead. Metallic lead, in quantities of several tens of grams, was loaded into the big oven of the ion source. After the source and the collectors were fixed to the setting flange of the vacuum chamber and the latter was evacuated to a pressure of $2\text{-}1 \cdot 10^{-5}$ mm Hg, the separation apparatus was put into operation. First of all, the magnetic field, the heater of the ion-source oven and the cathode with electron preheating were switched on.

TABLE 1

No. of expt.	Beam current, ma	Final isotope concentrations, %			Enrichment factor	
		Pb^{208}	Pb^{207}	Pb^{206}	for Pb^{208}	for Pb^{207}
1	15—17	99.1 11.5	0.6 87.4	0.3 1.1	100 —	— 26
2	8—13	98.8 12.6	0.9 85.5	0.3 1.9	75 —	— 22
3	9—11	99.7 4.4	0.2 95.0	0.1 0.6	302 —	— 71

At an oven temperature of about 800°C the discharge potential was switched on, as a result of which an arc discharge in the lead vapor was initiated. Further, after the switching on of the accelerating voltage by means of adjustment of the lead vapor pressure, the current and voltage of the discharge, the focussing field, and also after the adjustment of the ion source, the focussing of the ion beam was carried out. The control of the quality of the focussing was carried out through the presentation of the mass spectrum on the cathode-oscillograph screen. When the quality of the focussing was satisfactory (Fig. 7), the periodic displacement of the ion beam was stopped and by a smooth variation of the accelerating potential, or of the magnetic field, the ion beam was aimed at the correct place of the collector, either visually or with the help of the electron indicator. One of the beams "free" of separation was used for controlling the quality of the focussing during the collection period. Next,

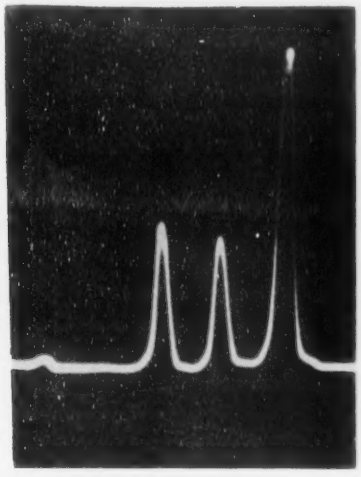

Fig. 7. Mass spectrum of lead.

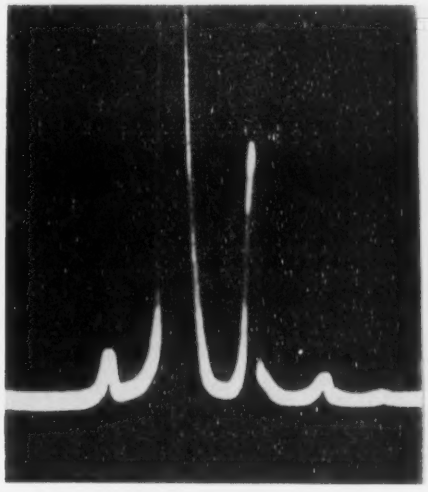

Fig. 8. Mass spectrum of plutonium.

the collector shutter was opened and the process of isotope collection was started which continued until all the lead was evaporated from the oven. The regulation of the collection process was reduced to gradually increasing the oven temperature to maintain the vapor pressure in the discharge chamber of the source at a constant value. The collecting assembly of the collector, in this case, consisted of two graphite chambers for the simultaneous collection of two neighboring isotopes.

TABLE 2

No. of expt.	Final concentrations, %		Enrichment factor for U^{238}
	U^{238}	U^{235}	
1	99.9963	0.0037	192
2	99.9958	0.0042	151
3	99.9970	0.0030	214
4	99.9963	0.0037	192
Average	99.9965	0.0035	194

TABLE 3

No. of expt.	Final concentrations, %				Enrichment factor for U^{236}
	U^{238}	U^{236}	U^{235}	U^{234}	
1	9.0	90.4	0.6	~0.01	1330
2	6.0	90.5	3.4	~0.1	1420
3	6.0	87.4	6.5	~0.04	985
Average	7.0	89.5	3.7	0.05	1240

TABLE 4

No. of expt.	Final concentrations, %			Enrichment factor		
	Pu^{239}	Pu^{240}	Pu^{241}	for Pu^{239}	for Pu^{240}	for Pu^{241}
1	100	73	—	1000	240	—
2	—	70	—	—	210	—
3	—	90	50	—	190	160
4	—	97	80	—	300	360

The results of several experiments on the collection of Pb^{207} and Pb^{208} isotopes from a naturally-occurring mixture are given in Table 1. Here, the enrichment factor means the ratio of the relative abundances of the isotope after and before separation.

From the mass-spectrogram (Fig. 7) it is seen that the apparatus is at the same time a "luminous" mass spectrometer. Its resolving power is about 1000 for beam currents of 10-15 ma; for currents of 1 ma and less, its resolving power is considerably higher.

Uranium. The tetrachloride of the naturally-occurring mixture of uranium isotopes, in quantities of several tens of grams, was loaded into the big oven of the ion source. Using the operations analogous to those used for the separation of lead isotopes, the apparatus was put into operation. The oven temperature in this case was about 450°C. The collecting assembly, as in the previous case, consisted of two chambers: for the collection of isotope U^{238} and for the simultaneous collection of isotopes U^{235} and U^{234}. The results of collection of isotope U^{238} are shown in Table 2.

Similar methods were used for the separation of isotope U^{236} from the mixture. The collecting assembly in this case consisted of three chambers for the separation of isotopes U^{235}, U^{236}, and U^{238}. The results of these experiments are shown in Table 3.

The high enrichment factor, obtained for the separation of U^{236}, was attained because the experiments were carried out with great care.

Plutonium. For the separation of plutonium isotopes the working substance was plutonium trichloride. In view of the different samples, both with regard to quantity and isotopic composition, of the raw mixture of plutonium isotopes at our disposal the working substance was either loaded into the big or the small oven of the source. In the latter case, the big oven was loaded with lead which served as the auxiliary substance for

maintaining the operating conditions of the arc discharge and for the adjustment of the apparatus. The vaporization temperature of the working substance was about 900°C. The collecting assemblies had up to five chambers for the various isotopes.

The mass spectrum of one of the samples of the raw mixture is shown in Fig. 8. From left to right are the maxima corresponding to the isotopes Pu^{238}, Pu^{239}, Pu^{240}, and Pu^{241}.

Table 4 gives some of the results of the separation of plutonium isotopes.

In view of the toxicity of the working substance, the exchange of sources and collectors was carried out with the help of the rubber air locks mentioned above.

The work was completed in 1953. Some of the separated plutonium isotopes were used in the work of Adamchuk et al.[2]. The isotope U^{236} was used in the work of Baranov et al. [3].

We express our gratitude to the personnel of the laboratory who took part in the work and also to G. N. Iakovlev and his collaborators for the preparation of the working substances and for the extraction of the separated isotopes.

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* Original Russian pagination. See C. B. translation.

** See English translation.

ACCELERATORS WITH SIMILAR ORBITS

A. A. Kolomenskii

We obtain the conditions that must be satisfied by a magnetic system in order that the frequencies of radial and vertical betatron oscillations be independent of the particle momenta (in this case the orbits are called dynamically similar). In such systems there should in principle be no excitation of betatron oscillations associated with synchrotron oscillations and other phenomena. A magnetic field $H_0(\theta)(r_0/r)^{n_0}$ with n_0 = const produces both geometric and dynamic similarity of the orbit. In weak-focusing accelerators with segments (race tracks) and in strong-focusing proton synchrotrons, the orbits are not dynamically similar. In order to obtain this kind of similarity in the first case, in addition to n_0 = const it is necessary that the magnet sectors have a common center. Different types of annular synchrocyclotrons are considered. In the first type the centers of neighboring magnet sectors are located on different sides of the doughnut and in the second type at the same point (at the center of the accelerator). In the second type the orbits are dynamically similar, unlike those of the first. It is shown that it is possible to design an annular synchrocyclotron in which the particles can move with stability simultaneously in both directions within the doughnut.

In all cyclic accelerators there exists at any time a family of closed orbits depending on a single parameter, the particle momentum p. Let $Q_{\rho,z}$ denote the number of radial and vertical betatron oscillations about these orbits in one revolution. For definite values of the $Q_{\rho,z}$, in particular in the linear approximation for

$$Q_{\rho,z} \approx k_{\rho,z},\quad Q_{\rho,z}=k_{\rho,z}\pm\frac{1}{2},\quad Q_\rho \pm Q_z \approx k \tag{1}$$

(where $k_{z,\rho}$ and k are integers) there arise dangerous resonance phenomena [1].

In all presently operating and projected accelerators (weak and strong focusing) synchrotron momentum oscillations are accompanied by periodic changes in the $Q_{\rho,z}$, caused by approach to resonance values and leading to excitation of betatron oscillation [1-3]. Variation of the $Q_{\rho,z}$ takes place also in the injection process, and in extracting and indicating the beam.

The question arises as to whether variations of the $Q_{\rho,z}$ due to changes of p are unavoidable or whether it is possible to give systems such that for different orbits (different momenta) the $Q_{\rho,z}$ remain constant within tolerance limits, that is,

$$Q_\rho = \text{const},\quad Q_z = \text{const}. \tag{2}$$

In such systems there can in principle occur none of the above-mentioned harmful betatron oscillations. Orbits which satisfy requirement (2) shall be called dynamically similar.

In the present article we derive the conditions which must be satisfied by the magnetic system in order that (2) be fulfilled, and consider separate special cases.

The equations of small betatron oscillations ρ, z about a closed orbit are [1]

$$\left.\begin{aligned} \frac{d^2\rho}{d\vartheta^2} + \frac{r_L^2}{R^2(\vartheta)}[1 - n(\vartheta)]\rho = 0, \\ \frac{d^2z}{d\vartheta^2} + \frac{r_L^2}{R^2(\vartheta)}\, n(\vartheta)\, z = 0, \end{aligned}\right\} \tag{3}$$

where $\vartheta = \frac{\sigma}{r_L} = 2\pi\frac{\sigma}{L}$ is the generalized azimuth angle, σ is the arc length along an orbit, r_L is the "orbit radius," R is its radius of curvature, L is the orbit length, and $n(\vartheta)$ is the field index, given by

$$n(\vartheta) = -\frac{R(\vartheta)}{H(\vartheta)}\frac{\partial H}{\partial \rho} \tag{4}$$

(where $\frac{\partial H}{\partial \rho}$ is the derivative along the normal to the orbit).

Equations (3) have solutions of the form

$$y = Ae^{i\mu m} f(\vartheta) + \text{ c. c.}, \quad f(\vartheta_0) = e^{i\mu} f(0)\ (y = \rho, z), \tag{5}$$

where μ is an eigenvalue ($Q = N\mu/2\pi$), $\vartheta_0 = 2\pi/N$ is the period of the system, m is the ordinal number of the element of periodicity, and c.c. indicates the complex conjugate quantity.

In order that (2) be fulfilled, let us require that the coefficients of ρ and z in Eq. (3) be the same for different orbits at a given point ϑ. This leads to the conditions

$$n_I(\vartheta) = n_{II}(\vartheta) = \ldots = \text{const}, \tag{6}$$

$$\left[\frac{r_L}{R(\vartheta)}\right]_I = \left[\frac{r_L}{R(\vartheta)}\right]_{II} = \ldots = \text{const}, \tag{7}$$

where the indices I, II, . . . refer to different orbits.

Condition (7) is satisfied if the closed orbits are geometrically similar. Therefore, we shall consider a system whose element of periodicity is composed of separate sectors (1, 2, . . ., k) having a common center O, such that the boundaries between the sectors are directed along the appropriate radius vectors.*

We shall consider the field in separate sectors to be axially symmetric, so that $H = H_k(r)$ does not depend on the azimuth angle θ (here k is the sector number). We shall find the form of $H_k(r)$ which leads to geometric similarity of the orbits, which means that one of the following conditions is fulfilled:

a) the angles γ between the radius vectors and the normal to the orbit are the same for different orbits, that is,

$$\gamma_I = \gamma_{II} = \ldots = \text{const}; \tag{8}$$

b) or for two arbitrary orbits the ratio of the radius vectors r, as well as of the radii of curvature R, is independent of the azimuth, or

$$\frac{r_I(\vartheta)}{r_{II}(\vartheta)} = \text{const}, \quad \frac{R_I(\vartheta)}{R_{II}(\vartheta)} = \text{const}. \tag{9}$$

* We shall not here consider systems in which the magnetic field is spiral [4].

The azimuthal component of the momentum $p_\theta = mr\dot{\theta}$ at any time satisfies the relation

$$p_\theta(r, z) = \frac{1}{r}\left[D + \frac{e}{c}\int_0^r H_z(z, \xi)\,\xi\,d\xi\right], \tag{10}$$

where D = const is the first integral of motion given by the initial values t_i, r_i, z_i and $p_{\theta i}$. In the given case $z \equiv 0$. From (10) it follows that

$$\cos\gamma = \frac{p_\theta}{p} = \frac{1}{1+x}\left\{(1+x_i)\frac{p_{\theta i}}{p} + \right.$$
$$\left. + \int_{1+x_i}^{1+x} \frac{H[r_p(1+\xi)]}{H(r_p)}(H\xi)\,d\xi\right\}, \tag{11}$$

where

$$x = \frac{r - r_p}{r_p}; \quad p = \frac{e}{c}H(r_p)\,r_p; \tag{12}$$

and r_p is the equilibrium radius of a sector.

From (8) and (10)-(12) we find that H(y) is in general a homogeneous function

$$H(by) = b^g H(y) \quad \text{(where g is an integer)}, \tag{13}$$

or must be of the form

$$H(r) = H_0(\theta)\left(\frac{r_0}{r}\right)^{n_0(\theta)}, \quad \frac{\partial n_0}{\partial r} = 0. \tag{14}$$

Since each orbit corresponds to a definite particle momentum, we find that for all azimuths

$$\frac{[H(\theta)\,R(\theta)]_I}{[H(\theta)\,R(\theta)]_{II}} = \text{const}, \tag{15}$$

and with this (9) and (14) lead to the fact that n_0, which we may call the geometric field index, must also be azimuth independent, that is,

$$n_0(\theta) = \text{const}, \quad n_0 = -\frac{r}{H}\frac{\partial H}{\partial r}. \tag{16}$$

Thus, the requirement of geometric similarity of the orbits is satisfied by a system whose element of periodicity is composed of sectors whose magnetic fields are of the form

$$H_k(r) = H_{0k}\left(\frac{r_0}{r}\right)^{n_0}, \quad n_0 = \text{const}. \tag{17}$$

The quantities H_{0k} may differ, some being positive, some negative, and some zero.

It is easily seen that Condition (17), as well as (8) and (9) which follow from it, also lead to fulfillment of (6) in view of the relation

$$n(\vartheta) = \frac{R(\vartheta)\cos\gamma(\vartheta)}{r(\vartheta)}\,n_0. \tag{18}$$

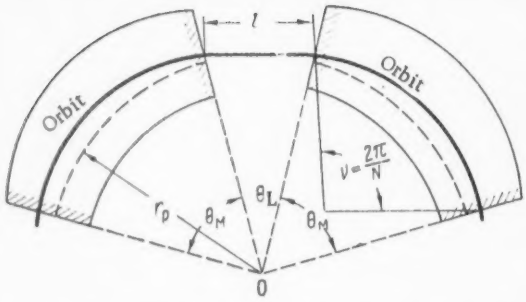

Fig. 1. Diagram of a weak-focusing segmented accelerator (racetrack).

Thus, the closed orbits associated with (17) are geometrically and dynamically similar.*

At the edges of the magnetic sectors and in the field-free sections there arise additional edge effects. If the edge makes an angle γ_{edge} with the normal to the orbit, then as is well known [5, 6] on passing through the edge the orbit is bent through additional angles $\delta\nu_\rho$ in the z = 0 plane and $\delta\nu_z$ in the vertical plane:

$$\delta\nu_\rho \approx -\frac{\rho}{R}\operatorname{tg}\gamma_{edge}, \delta\nu_z = \frac{z}{R}\operatorname{tg}\gamma_{edge}. \qquad (19)$$

This causes the values of the $Q_{\rho,z}$ to change somewhat, but since γ_{edge} remains the same for similar orbits, these changes are the same for all orbits.

Presently used accelerators do not satisfy the conditions of geometric and dynamic similarity. This is true both of weak-focusing segmented accelerators (racetracks) and of strong-focusing proton synchrotrons under construction. In the latter instruments, $n_1 \approx -n_2$, whereas similarity requires $n_1 = n_2$.

In order that the $Q_{\rho,z}$ in a racetrack-type system be independent of the particle energy, it is necessary in addition to n_0 = const that the sectors have a common center. Then the length of each of the linear sections will change in proportion to the radius vector (Fig. 1). Each of the orbits will make an angle $\chi_{edge} = \theta_L/2$, with the normal to the sector edge, where θ_L is the angular aperture of the field-free section. In a track with similar orbits, the common values of the $\mu_{\rho,z}$ of Eq. (5) for all orbits are given, taking into account edge effects, by the expression

$$\cos\mu_{\rho,z} \approx c_{\rho,z} - \varkappa_{\rho,z} s_{\rho,z} \operatorname{tg}\frac{\theta_L}{2} \pm \pm\frac{\operatorname{tg}\gamma_{edge}}{\varkappa_{\rho,z}}\left(\varkappa_{\rho,z}\, c_{\rho,z} \operatorname{tg}\frac{\theta_L}{2} + s_{\rho,z}\right), \qquad (20)$$

where

$$c = \cos\varkappa\theta_M; \quad s = \sin\varkappa\theta_M; \quad \varkappa^2_{\rho,z} = \begin{cases} 1-n_0 \\ n_0 \end{cases} \qquad (21)$$

(here θ_M is the angular aperture of the magnetic sector).

A strong-focusing accelerator ($|n| \gg 1$) satisfying Condition (2) can be obtained if the field directions in neighboring centers are opposite, that is, if $H_1 > 0$, $H_2 < 0$ (with a common value of n_0). An accelerator having oppositely directed fields and a time-constant field (annular synchrocyclotron) was first suggested by the author together with Petukhov and Rabinovitch in 1953 [7] (see also [8]).** In the first type the centers of neighboring sectors were located alternately on both sides of the doughnut (Fig. 2a). Such a system, however, does not satisfy (2). Therefore, the author proposed [9] another type of annular synchrocyclotron which may be called "central" (see also [10]). In this type the centers of the sectors are at a common point, the center of the instrument, and the signs of the fields within the sectors alternate as before, but the form of the field (Fig. 2b) satisfies (17). It is clear that the "central" type is an accelerator with geometrically and dynamically similar orbits.

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* We note that the case in which $H(\theta)$ = const in (14) and the closed orbits are circles is degenerate: in this case the orbits are always geometrically similar. Dynamical similarity of the orbits, however, still requires that (17) be fulfilled.

** The advantages of an annular accelerator with a time-constant field have been described elsewhere [7, 9].

*** [In this paper 'tg' ≡ 'tan,' 'sh' ≡ 'sinh,' 'ch' ≡ 'cosh' — Publisher.]

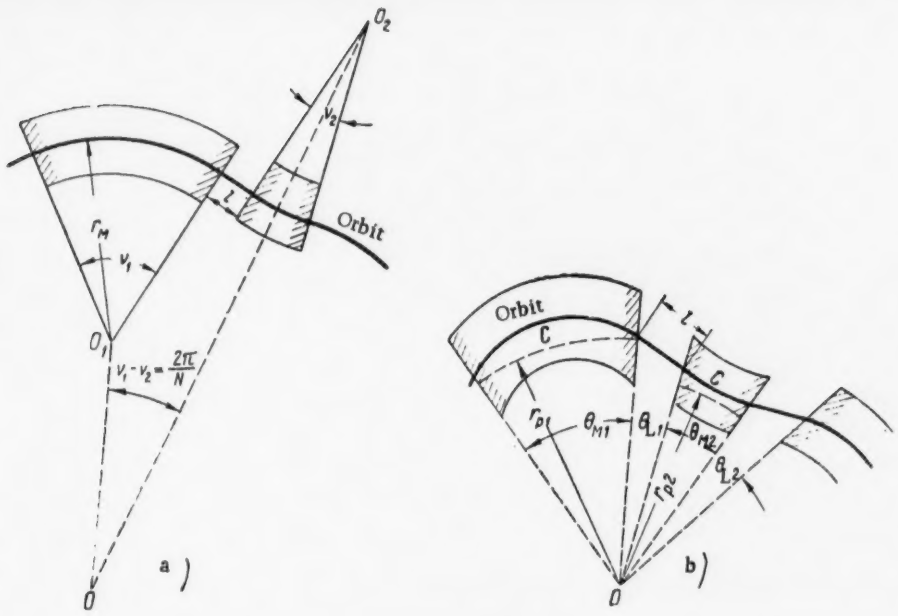

Fig. 2. Diagrams of annular synchrocyclotrons. a) The centers of the sectors are on opposite sides of the orbit; b) the centers of the sectors are at a common point.

Let us investigate the motion of particles in such an instrument in more detail, considering an element of periodicity composed of four sections (Fig. 2b), so that

$$\theta_0 = \theta_{M1} + \theta_{L1} + \theta_{M2} + \theta_{L2} = \frac{2\pi}{N}. \tag{22}$$

First, we must find the family of closed orbits for the given values of the parameters H_{0k}, θ_{Mk}, θ_{Lk}, and n_0 (k = 1, 2).

The expression for the sections of the orbits within the sectors can be written, bearing in mind (10), in the form

$$\theta = \int_{x_{1,2}}^{x} \frac{F_{1,2}(\xi)\, d\xi}{(1+\xi)\sqrt{1-F_{1,2}^2(\xi)}}, \tag{23}$$

where

$$F_{1,2}(x) = \frac{1}{1+x}\left\{1 + x_{1,2} \pm \right.$$
$$\left. \pm \frac{1}{2-n_0}\left[(1+x)^{2-n_0} - (1+x_{1,2})^{2-n_0}\right]\right\}, \tag{24}$$

and the variable $\underline{x}$ is given by (12). The quantities $x_{1,2}$ correspond to the points C at which the orbit is reversed and give the furthest and nearest distances of the orbit from the center:

$$\left.\frac{dr}{d\theta}\right|_{r=r_c} = 0, \quad p\theta(r_c) = \pm p. \tag{25}$$

In order to relate the parameters which characterize the orbit in both sectors, we make use of angular momentum conservation in the field-free regions, obtaining

$$r_{p1}(1 + x_{edge1})F_1(x_{edge1}) = r_{p2}(1 + x_{edge2})F_2(x_{edge2}), \tag{26}$$

where $x_{edge\,1,2}$ is the value of $\underline{x}$ (for the orbit) on the edges of the sectors. If there are no linear sections and if $H_{01} = |H_{02}|$, then x_{edge} is given by

$$x_{edge} = \left\{\frac{1}{2}\left[(1+x_1)^{2-n_0} + (1+x_2)^{2-n_0} + \right.\right.$$
$$\left.\left. + (2-n_0)(x_2 - x_1)\right]\right\}^{\frac{1}{2-n_0}} - 1. \tag{27}$$

We now introduce the dimensionless variables

$$s = \frac{\sigma}{r_{p1}}, \quad u = \frac{\rho}{r_{p1}}, \quad y = \frac{z}{r_{p1}}, \quad w_{1,2}^2 = \left\{\left(\frac{H_{01}}{H_{02}}\right)^2\right. \tag{28}$$

and make use of (18), so that Eqs. (3) are transformed to

$$\frac{d^2u}{ds^2} + q_\rho(s)\,u = 0, \quad [q_\rho(s)]_{1,2} =$$
$$= \frac{1 \mp \dfrac{F_{1,2}(x_M(s))}{[1+x_M(s)]^{1-n_0}}\,n_0}{w_{1,2}^2\,[1+x_M(s)]^{2n_0}}; \tag{29}$$

$$\frac{d^2y}{ds^2} + q_z(s)\,y = 0, \quad [q_z(s)]_{1,2} =$$
$$= \frac{\pm F_{1,2}(x_M(s))\,n_0}{w_{1,2}^2\,[1+x_M(s)]^{1+n_0}}, \tag{30}$$

where the upper sign refers to the first sector, and the lower to the second (with opposite curvature), and $x_M(s)$ describes a closed orbit. The variable $\underline{s}$ is related to the azimuth angle by the expression

$$s = w_{1,2}\int_{\theta_{init}}^{\theta} \frac{1 + x_M(\xi)}{F_{1,2}(x_M(\xi))}\,d\xi. \tag{31}$$

The shape of the closed orbit and the magnitudes of the $q_{\rho,z}(s)$ and the $\mu_{\rho,z}$ depend on the parameters N, n_0, $\frac{\theta_{M2}}{\theta_{M1}}$, and $w_2 = \frac{H_{01}}{H_{02}}$. Solving Hill's Eqs. (29) and (30) we obtain $f_{\rho,z}(s)$ and $\mu_{\rho,z}$ for our case. Knowing the shape of the field and having expressions for μ and $\underline{f}$, equations previously derived [1] can be used to find all the necessary characteristics of the motion: the amplitude envelope, the resonance width, tolerances, nonlinear effects, etc.

It may be quite difficult and inconvenient to find f(s) and μ by numerical integration of Eqs. (29) and (30), especially when a large number of different variants must be investigated. In this case one can obtain an approximate expression for $\cos \mu_{\rho,z}$ which is sufficiently good for practical uses by replacing the functions $q_{z,\rho}(s)$ by constant "average" values $\langle q_{\rho,z} \rangle$. With edge effects taken into account, calculation of the $\cos \mu_{\rho,z}$ leads to the expression

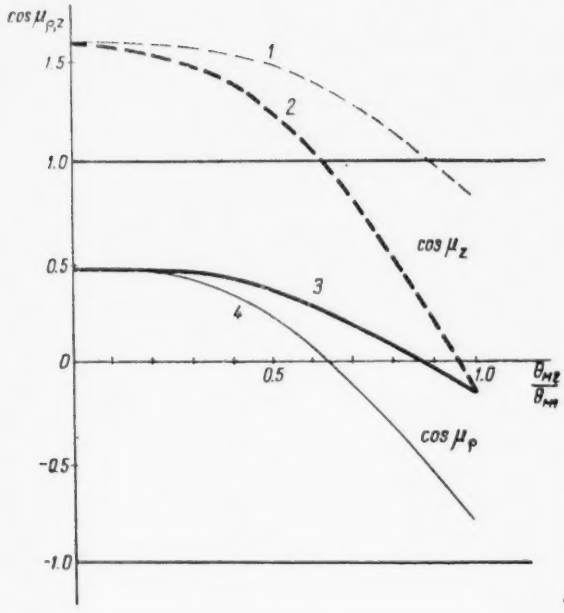

Fig. 3. The dependence of the $\cos \mu_{\rho,z}$ on the ratio $\frac{\theta_{M2}}{\theta_{M1}}$ ($N = 24$, $n_0 = -16$), accounting for (2, 3) and not accounting for (1, 4) edge effects.

$$\cos \mu_\rho = (\cos \mu_\rho)_{\delta \nu_\rho = 0} + \\ + g_1 \left\{ \frac{\xi_1}{\xi_2} (\mathrm{sh} - \xi_2 \mathrm{ch}) \left(c + \frac{g_1 s}{2} \right) + \right. \\ \left. + (\mathrm{ch} + \xi_2 \mathrm{sh}) \left(s + \xi_1 c + \frac{g_1 \xi_1}{2} s \right) \right\} + \\ + g_2 \left\{ \frac{\xi_2}{\xi_1} (s + \xi_1 c) \left(\mathrm{ch} + \frac{g_2 \mathrm{sh}}{2} \right) + \right. \\ \left. + (c - \xi_1 s) \left(\mathrm{sh} + \xi_2 \mathrm{ch} + \frac{g_2 \xi_2 \mathrm{sh}}{2} \right) \right\} + \\ + g_1 g_2 \{ g_1 \xi_1 (\mathrm{sh} + \xi_2 \mathrm{ch}) + g_2 \xi_2 (s + \xi_1 c) \} + \\ + \frac{g_1^2 g_2^2}{2} \xi_1 \xi_2 s \, \mathrm{sh}, \tag{32}$$

where

$$\left. \begin{aligned} c = \cos (\langle q_{\rho 1} \rangle^{1/2} s_1), \quad \mathrm{ch} = \mathrm{ch} (\langle q_{\rho 2} \rangle^{1/2} s_2), \\ \xi_{1,2} = \langle q_{\rho 1,2} \rangle^{1/2} s_0, \quad g_{1,2} = \frac{\mathrm{tg} \, \gamma_{\mathrm{edge}1,2} r_{\rho 1,2}}{\langle q_{\rho 1,2} \rangle^{1/2} R_{1,2}}, \end{aligned} \right\} \tag{33}$$

and $(\cos \mu_\rho)_{\delta \nu_\rho = 0}$ is the value of $\cos \mu_\rho$ in the absence of edge effects, namely

$$(\cos \mu_\rho)_{\delta \nu_\rho = 0} = c \, \mathrm{ch} + \xi_2 c \, \mathrm{sh} - \xi_1 s \, \mathrm{ch} + \\ + \frac{\xi_2^2 - \xi_1^2}{2 \xi_1 \xi_2} - \frac{\xi_1 \xi_2}{2} s \, \mathrm{sh}. \tag{34}$$

The expression for $\cos \mu_z$ is similar.

As an example, Fig. 3 gives the $\cos \mu_{\rho,z}$ as a function of $\frac{\theta_{M2}}{\theta_{M1}}$ for fixed N and n_0, obtained with the aid of (32). For comparison, we give also the values of the $\cos \mu_{\rho,z}$ as obtained without taking into account edge effects. It is seen that these effects can cause the frequencies $\mu_{\rho,z}$ to increase greatly. This is particularly true for relatively small instruments (with small values of N and n_0), although edge effects may not be neglected either in large instruments. For $N = 60$, and $n_0 = -100$, and $\frac{\theta_{L1}}{\theta_{M1}} = \frac{1}{3}$, for instance, we obtain

$$(\cos \mu_\rho)_{\delta \nu_\rho = 0} = -0.10, \quad \cos \mu_\rho = 0.04, \\ (\cos \mu_z)_{\delta \nu_z = 0} = 0.99, \quad \cos \mu_z = 0.78.$$

Figure 3 shows that stability ($|\cos \mu_{\rho,z}| < 1$) is obtained in a certain interval of $\frac{\theta_{M2}}{\theta_{M1}} = b$. In particular, there exist values of b such that stability occurs also for $\frac{1}{b}$. This means that particles can move with stability both clockwise and counter-clockwise. This situation leads to the possibility of designing an instrument in which it is possible to accelerate beams of similar particles in opposite directions. In such an instrument, which was first proposed by the author [11] for the case $b = 1$ and was called a "symmetric" annular synchrocyclotron, one can achieve multiple collisions of oppositely directed beams of relativistic particles. As is well known, such collisions lead to a large gain in the energy used in the physical experiment, such as for the creation of new particles.

In conclusion the author takes this opportunity to express his gratitude to L. L. Sabsovich for discussing the results of the work, and to G. I. Kharlamova for performing many numerical calculations.

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ANGULAR DISTRIBUTION OF ELASTICALLY AND INELASTICALLY SCATTERED 2.9-Mev NEUTRONS

V. I. Popov

A hydrogen ionization chamber and annular geometry are used to measure the angular distribution of elastically and inelastically scattered 2.9-Mev neutrons, as well as inelastically scattered neutrons associated with excitation of various levels or groups of levels of iron, copper, lead, and bismuth nuclei. The integral cross sections for elastic and inelastic scattering are presented, as are the transport cross sections. The experimental results are compared with theoretical calculations based on the optical model. It is noted that the angular distribution of elastically scattered neutrons from atoms with almost equal atomic weights may be quite different.

INTRODUCTION

Much attention has been paid of late to the study of angular distributions and spectra of scattered neutrons. The results of such experiments are very important to the understanding of the mechanism of nuclear reactions and nuclear structure. From an analysis of the angular distributions of inelastically scattered neutrons under conditions in which the statistical theory is applicable to the compound nucleus, one can determine the spins and parities of the final nucleus [1]. Data on the angular distribution of elastically and inelastically scattered neutrons can be used to verify the validity of various nuclear models and to indicate directions for their further refinement. Finally, all these experimental data are used in reactor calculations.

The purpose of the present work was to obtain data on the angular distribution of scattered monochromatic neutrons whose energy is 2.9 Mev while simultaneously measuring their spectra.

Method of Measurement and Apparatus

The angular distributions of the scattered neutrons were measured with an annular geometry (Fig. 1), and the scattering angle was varied by moving the ring and detector in the horizontal direction. The neutron source was a target of heavy ice bombarded by deuterons accelerated to an energy of 150 kev. The mean energy of the neutrons incident on the scatterer was 2.9 ± 0.1 Mev. The neutron detector was a spherical ionization chamber (Fig. 2) with an external electrode diameter of 13 cm, filled with a mixture of 5 atmos of hydrogen and 5 atmos of argon; this ionization chamber registered recoil protons. The spherical shape of the chamber minimizes the undesirable induction effect, which would otherwise alter the pulse spectrum of the recoil protons; in addition, this shape leads to an effeciency which is practically independent of the incident neutron direction. To aid electron collection, the gases were subjected to a preliminary purification of electronegative impurities by passing them through copper wool heated to 500°C and by adsorption on activated carbon at liquid nitrogen temperatures. In several cases the chamber was further purified, irradiating it by γ-rays while a potential was maintained on the electrodes.

An expecially constructed insulator (in the form of a guard ring) permitted operation of the chamber at a potential difference of 12 kv, which was necessary for complete charge collection.

In chambers of this type the fundamental factors altering the pulse spectrum are the wall effect and the induction effect [2]. Calculation shows that the pulse spectrum of the chamber, when it is irradiated by monochromatic neutrons of energies up to 3 Mev, should be of the form

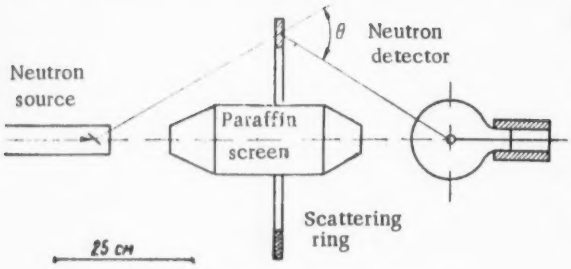

Fig. 1. Diagram of the experiment.

$$W(V_C) = \frac{1}{V_{C\max}} \frac{3(a-1)^3}{a[a^3-(a-1)^3]} \left\{ \left(1+\frac{\lambda(E_0)}{R_{cp}}\right) \times \right.$$
$$\times \left[\frac{1}{3(a-1)^3} + \frac{3}{2}\frac{1}{(a-1)^2} + \frac{3}{a-1} - \frac{1}{3}\frac{x^3}{(a-x)^3} - \right.$$
$$- \frac{3}{2}\frac{x^2}{(a-x)^2} - \frac{3x}{a-x} + \ln\frac{a-x}{x(a-1)} \Big] - \frac{2\lambda(E_0)\,x}{R_{cp}} \times$$
$$\times \left[\frac{1}{3(a-1)^3} + \frac{2}{(a-1)^2} + \frac{6}{a-1} - a - \frac{1}{3} \times \frac{x^3}{(a-x)^3} - \right.$$
$$\left. \left. - \frac{2x^2}{(a-x)^2} - \frac{6x}{a-x} + \frac{a}{x} + 4\ln\frac{a-x}{x(a-1)} \right] \right\},$$

if only these two effects are of importance, where V_C is the pulse amplitude, $V_{C\max}$ is the maximum pulse amplitude in the spectrum, and $a = \frac{R}{R-r_0}$; r_0 and R are the internal and external electrode radii, $R_{cp} = \frac{4}{3}R$ is a geometric factor, $\lambda(E_0)$ is the mean free path in the gas of a proton whose energy E_0 corresponds to that of the incident neutrons, and $x = \frac{V_C}{V_{C\max}}$.

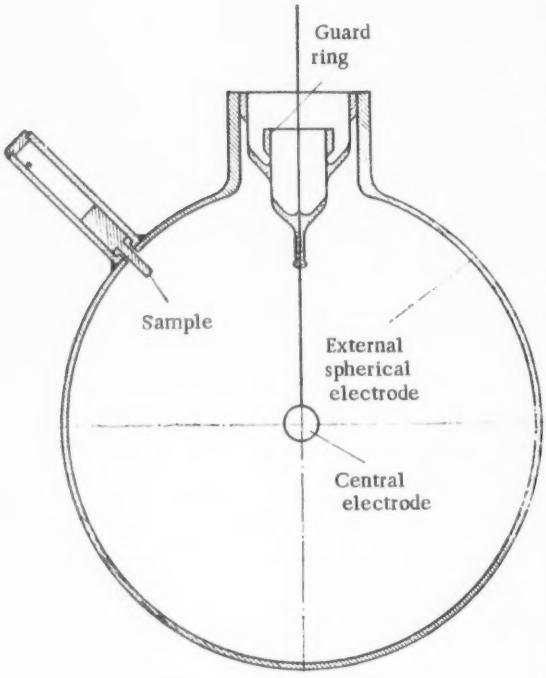

Fig. 2. Ionization chamber.

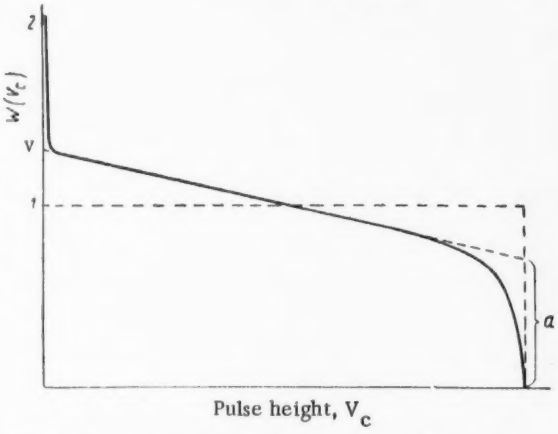

Fig. 3. Calculated pulse spectrum of recoil protons from monochromatic neutrons, including the wall effect and induction effect.

The pulse spectrum given by this equation is approximately a trapezoid with rounded-off corners (Fig. 3), and whose bases are in the ratio

$$\frac{b}{a} = \frac{R_{cp}+\lambda(E_0)}{R_{cp}-\lambda(E_0)}.$$

Over a large section, the measured chamber pulse spectrum (Fig. 4) can also be approximated by a trapezoid, but with a larger ratio of the bases than that given by the formula. This would seem to be due to other factors not accounted for. Therefore, the actual calculation of the intensity of neutron groups was performed on the basis of the following formula, obtained from the previous one by introducing the two constant coefficients α_1 and α_2:

$$\frac{b}{a} = \frac{R_{cp}+\alpha_1\lambda(E_0)}{R_{cp}-\alpha_1\lambda(E_0)}\alpha_2.$$

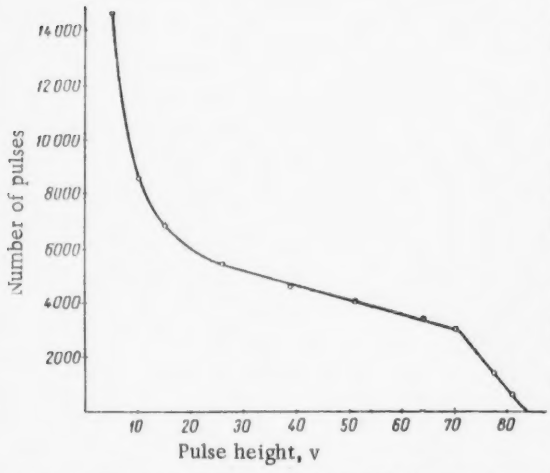

Fig. 4. Pulse spectrum of recoil protons from 3.0-Mev neutrons.

These coefficients were obtained experimentally by measuring two recoil proton spectra from 2.5 and 3.0-Mev monochromatic neutrons.

It was possible, with this chamber, to investigate the spectrum of neutrons with energies from 0.8 to 3.0 Mev with a resolving power of 7% in the energy. The pulses from the chamber were fed into a linear amplifier and recorded by a twenty-channel pulse-height analyzer.

The spectra obtained were treated by a ratio method involving division of the recoil proton spectrum from the scattered neutrons (after subtracting out the background) by the recoil proton spectrum from unscattered neutrons. In other words the number of pulses per channel in the first spectrum ($N_{p+bkgd} - N_{bkgd}$) is divided by the number of pulses in the same channed for the other spectrum (N_0). This method is convenient in that it leads to a step-like "ratio curve" each step of which gives the energy of a neutron group and whose height gives its intensity. In addition, this method makes it possible to find the differential cross sections for inelastic scattering in the same relative units for all scattering angles. One can then construct the corresponding angular distributions with a smaller relative error than when using absolute units. It should be noted that this method automatically eliminates some inaccuracies due to unequal analyzer channel widths or nonlinearity of the amplifier.

The treatment of the experimental data included the wall and induction effects (by the method described above), absorption and multiple scattering of neutrons in the samples, anisotropy of the source from the point of view of neutron intensity and energy, energy losses in elastic collisions, effects due to the paraffin screen shielding the detector from the direct beam, and the dependence of the detector efficiency on the incident neutron direction. These effects were accounted for by performing subsidiary experiments. In particular, in an attempt to eliminate absorption and multiple scattering effects, scattering rings of various thicknesses were used and the results were extrapolated to zero thickness.

RESULTS

Differential elastic scattering cross sections of 2.9-Mev neutrons were measured for iron, copper, lead, and bismuth in the range of scattering angles from 30° to 150° at intervals of 30° (and sometimes 15°). In addition, differential inelastic scattering cross sections were measured for excitation of several levels of these nuclei.

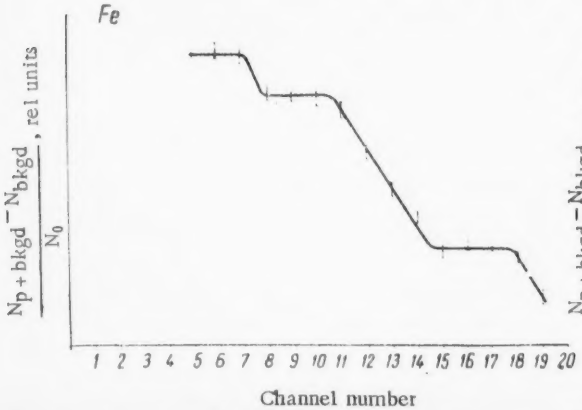

Fig. 5. Ratio curve for iron, at a scattering angle of 90°.

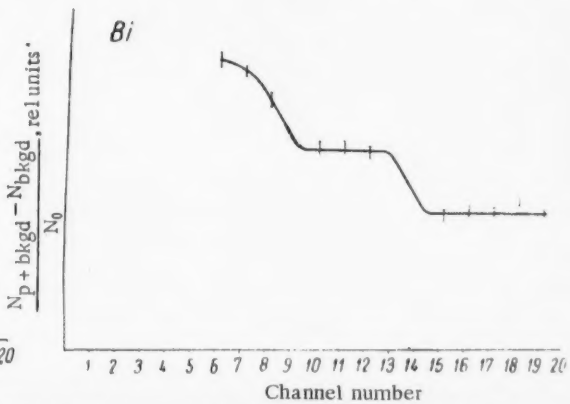

Fig. 6. Ratio curve for bismuth at a scattering angle of 140°.

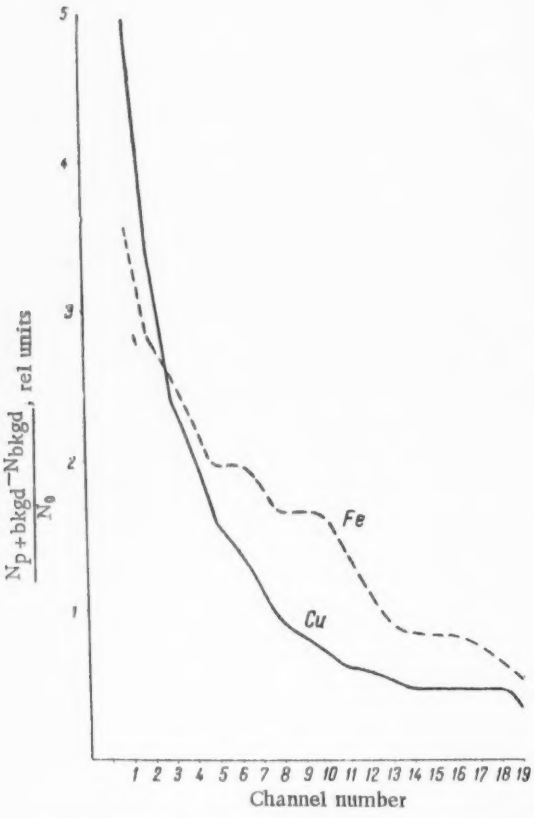

Fig. 7. Ratio curves for iron and copper at a scattering angle of 60°.

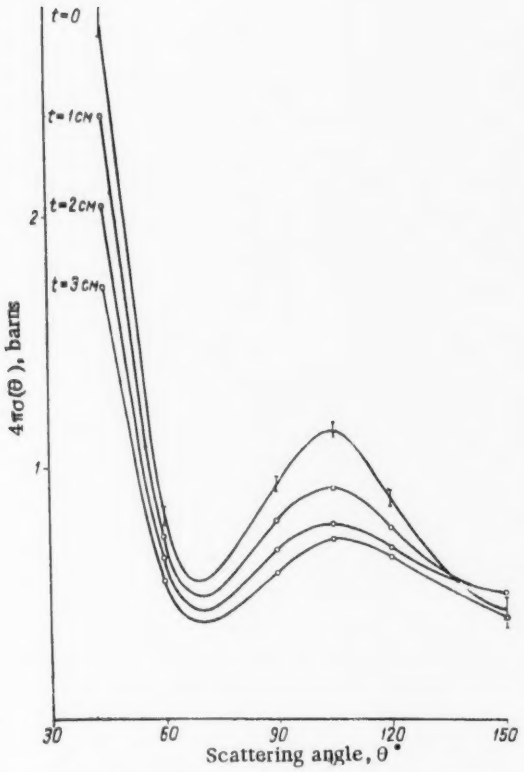

Fig. 8. Differential cross section for neutrons elastically scattered by copper nuclei.

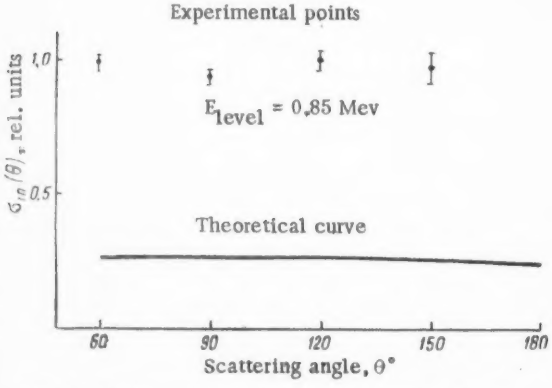

Fig. 9. Differential cross section for neutrons inelastically scattered by iron with excitation of the 0.85-Mev nuclear level.

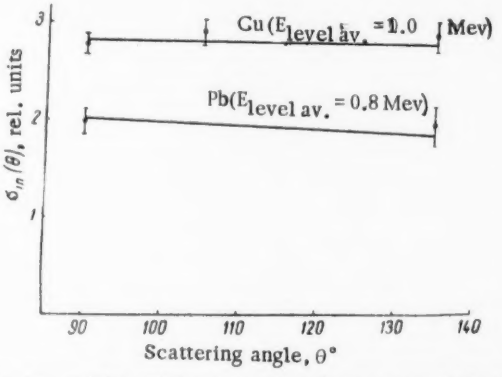

Fig. 10. Differential cross section for neutrons inelastically scattered by copper with excitation of energy levels with a mean energy of 1.0 Mev, and by lead with excitation of energy levels with a mean energy of 0.8 Mev.

TABLE 1

Elastic Scattering Cross Sections of 2.9-Mev Neutrons, $4\pi\sigma(\vartheta)$, barns

Element \ ϑ	30°	45°	60°	90°	105°	120°	150°
Fe	10.5±0.3	3.8±0.1	1.47±0.04	0.79±0.03	1.15±0.02	1.15±0.04	1.38±0.11
Cu	7.7±0.2	2.8±0.1	0.81±0.03	0.94±0.03		0.89±0.03	0.43±0.06
Pb	27.4±0.5	5.8±0.2	2.28±0.06	2.71±0.06		1.70±0.05	3.2 ±0.1
Bi	22.7±0.5	6.1±0.2	2.70±0.06	3.34±0.07		2.01±0.06	3.3 ±0.1

Figures 5 and 6 give the ratio curves for iron and bismuth. In both cases three neutron groups are well resolved. One of these is the elastically scattered group, and the other two are the inelastically scattered ones corresponding to excitation of the first two nuclear levels in iron and bismuth. These curves are the immediate experimental results. The ratio curve for copper (Fig. 7) can be used for satisfactory separation of the elastically scattered neutrons from the inelastically scattered ones, but the resolution is not sufficient to separate the latter into groups related to the two copper isotopes each of which has its own level system. The same reason made it difficult to resolve even the elastic scattering in lead.

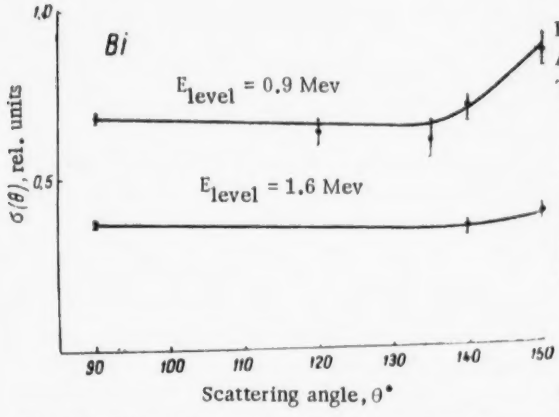

Fig. 11. Differential cross section for neutrons inelastically scattered by bismuth with excitation of the 0.9- and 1.6-Mev nuclear levels.

TABLE 2

Inelastic Scattering Cross Sections of Neutrons at an Angle of 90° with Excitation of Separate Levels of the Target Nucleus

Element	Nuclear energy level, Mev	$4\pi\sigma_{in}$ (90°), barns
Fe	0.85±0.07	0.93±0.05
Fe	1.54±0.07	0.12±0.03
Bi	0.90±0.07	0.68±0.04
Bi	1.56±0.07	0.37±0.04

For the measurements with lead, therefore, the chamber was used as a threshold detector to detect recoil protons with energies greater than 2.25 Mev. The contribution from inelastic scattering of neutrons was accounted for according to Sal'nikov's data [3].

The results of measurements are presented in Tables 1-3 and Figs. 8-11.

TABLE 3

Integral Cross Sections

Element	Experimental values, barns				Theoretical values, barns		
	σ_t [4]	σ_{el}	σ_{in}	σ_{tr}	σ_t	σ_{in}	σ_c
Fe	3.4±0.1	2.5±0.1	0.9±0.18	2.2±0.2	3.0	2.5	0.5
Cu	3.3±0.1	1.88±0.10	1.4±0.18	2.4±0.2	3.0	2.5	0.5
Pb	7.4±0.1	5.9±0.2	1.5±0.25	4.5±0.3	6.4	4.9	1.5
Bi	7.5±0.1	5.9±0.2	1.6±0.25	4.8±0.3	6.4	4.9	1.5

Table 3 gives the experimental values of the elastic scattering cross sections σ_{el} obtained by integration of the differential scattering curves, the transport scattering σ_{tr}, and the inelastic scattering σ_{in}, obtained as the difference between the total cross sections σ_t as given by Sal'nikov [3] and the elastic scattering cross sections. The same table gives the theoretical cross sections calculated using the complex potential model, as well as the cross section σ_c for formation of the compound nucleus.

DISCUSSION OF RESULTS

As is known, Feshbach, Porter, and Weisskopf have succeeded in explaining the energy dependence of the total neutron cross sections by using a complex potential of the form

$$V = -V_0(1+i\xi) \quad \text{for} \quad r < R,$$
$$V = 0 \quad \text{for} \quad r > R$$

(where R is the nuclear radius) in which the parameters have the values $V_0 = +42$ Mev, $\xi = 0.03$.

It is thus reasonable to compare the results obtained with calculations based on this potential. Figure 12 shows the experimental angular distributions of elastic neutron scattering by iron and copper nuclei, as well as the theoretical curve for iron (the theoretical copper curve is almost the same as that for iron). It is seen from the figure that the experimental and theoretical curves for copper are in good agreement, at least with respect to the positions of the maxima and minima. For iron, on the other hand, the theoretical curve differs greatly from the experimental one.

Comparison of the experimental curves for iron and copper shows that the angular distribution of elastically scattered neutrons may be quite different for atoms whose atomic weights are nearly the same. This has not been noted in previous work. Generally speaking, the theory allows for such a possibility due to elastic scattering with formation of a compound nucleus. The amount of such scattering should be determined by the internal structure of the nucleus and can be different for different elements, even though their atomic weights may be almost the same. It is not yet possible, however, to calculate this additional contribution to the elastic scattering, in view of the fact that although a simple rectangular complex potential explains some of the behavior of the total neutron cross section, it does not give the correct probability for formation of the compound nucleus. This has been shown previously in several works [5, 6] and is verified by the data in Table 3. The reason for this deviation, as is known, lies in the fact that a potential well with sharp edges leads to excess reflection of the neutron waves from the nuclear surface and is thus inapplicable for quantitative evaluations of the probabilities for processes that involve formation of the compound nucleus.

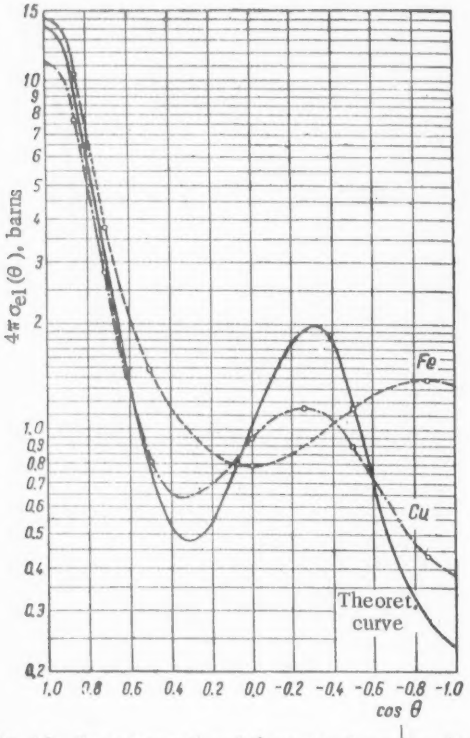

Fig. 12. Experimental and theoretical angular distributions for elastic scattering of 2.9-Mev neutrons by iron and copper.

P. E. Nemirovskii [7] has made an attempt to correct this situation by smoothing out the edges of the potential well in some definite way. He was able in this way to obtain much better agreement with experiment. But the use of a potential with a rounded-off edge leads to significant calculational difficulties, and we have therefore performed the calculation in the present work using a rectangular potential well with a single choice of the parameters.

Nevertheless, comparison of the theoretical and experimental curves gives some basis to the hypothesis that elastic scattering with formation of the compound nucleus is not great in copper. Even without accounting for it, satisfactory agreement between theory and experiment is obtained. In iron, on the other hand, this process probably has a high probability; this explains the large difference between this angular distribution and that of copper. This is implied also by the value of the integral elastic scattering cross section, which is 0.6 barns greater for iron than it is for copper. At the same time the inelastic scattering cross section for iron is smaller than that of copper by about the same amount, so that the total cross sections for these elements are about the same at the given energy. The angular distribution for elastic neutron scattering with formation of the compound nucleus has been calculated according to Houser and Feshbach [1] (Fig. 13), and like the experimental angular distribution for elastic scattering by iron it has a minimum at 90°, increasing for larger angles. This tends to support the above hypothesis. Thus, the even-even Fe^{56} nucleus would seem to be more stable with respect to excitation than the Cu^{63} and Cu^{65} nuclei, which are even-odd.

If one accepts the above explanation, it becomes understandable that several authors observe no significant difference in the behavior of nuclei with almost equal masses in studying the angular distribution for neutron energies of 1.0 Mev [8, 9], and 4.1 Mev [6]. At a neutron energy of 1.0 Mev, in fact, the inelastic scattering cross sections, although very different for different elements, are too small for observable changes to occur in the elastic scattering cross section due to formation of the compound nucleus. They can thus hardly alter the magnitudes and angular distributions of elastic scattering as a whole. At a neutron energy of 4.1 Mev elastic scattering with formation of compound nucleus is quite small, since the compound nucleis can decay in many other ways.

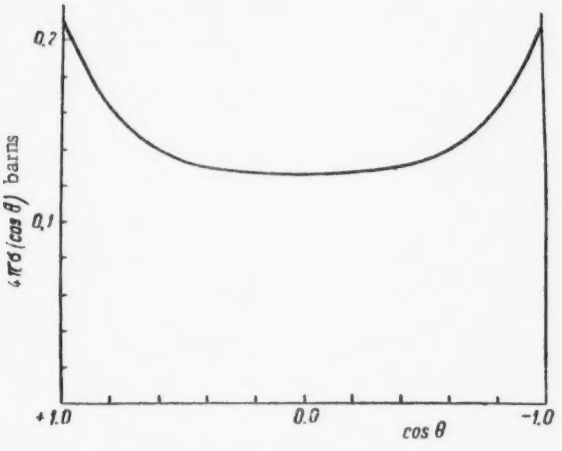

Fig. 13. Theoretical angular distribution of neutrons elastically scattered by iron nuclei with formation of a compound nucleus.

It should be noted that these are the only differences in the scattering of 2.9-Mev neutrons by iron and copper. The ratio curves of Fig. 7 for a scattering angle of 60° characterize the neutron spectra scattered by each of these nuclei. It is easily seen that in iron it it primarily the first level that is excited by inelastic scattering; the higher levels are excited only weakly. In copper the opposite is true. The higher levels are more strongly excited, and the lower more weakly, which verifies the more recently published results of Cranberg and Levin [10].

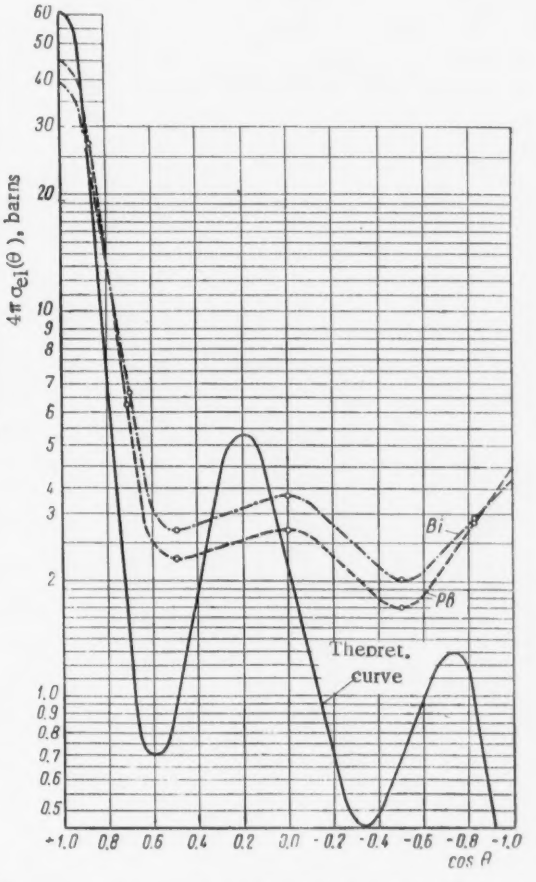

Fig. 14. Experimental and theoretical angular distributions of 2.9-Mev neutrons elastically scattered by lead and bismuth.

In addition to the experimental angular distribution of inelastically scattered neutrons from the 0.85-Mev level in iron, Fig. 9 gives the theoretical distribution as calculated by the Houser-Feshbach theory. The spins and parities of the ground level and the first two excited states which were used in this calculation were those obtained for Fe^{56} from an analysis of experimental data by Poppema and co-workers [11], namely 0^+, 2^+, 4^+. It is seen from the figure that the theoretical and experimental values differ greatly, as may have been expected, although the deviation from isotropic scattering is quite small for both.

The angular distribution curves for elastic neutron scattering by lead and bismuth (Fig. 14) are very similar, but except for the number of maxima they have little in common with the theoretical distribution. The deviation is particularly great at large scattering angles, where the experimental values are much greater than the calculated ones. It should be recalled again that it is just for these angles that elastic scattering with formation of the compound nucleus becomes more significant. In the present case this process is very probable since the number of neutrons in these elements is magic, and in Pb^{208} this is true both of the neutron and proton numbers. Therefore, the previous considerations with respect to even-even iron nuclei are applicable for these.

The only inelastic angular distribution with an observable anisotropy is that from the 0.9-Mev level of bismuth. The general rules for the shell model as given by Pryce [12] can be used to show that this corresponds to a transition in bismuth from a ground state with spin $^9/_2$ to an excited state with spin $^7/_2$, and is thus a transition between states with high spin.

In conclusion the author thanks Acting Member of the Academy of Sciences, USSR, A. I. Leipunskii for directing the work, Candidate of Physical-Mathematical Sciences, A. N. Serbinov who operated the high-voltage apparatus, and V. S. Stavinskii for discussing the results.

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THE MEASUREMENT OF THE RESONANCE INTEGRALS FOR NEUTRON ABSORPTION

V. B. Klimentov and V. M. Griazev

The results of the measurement of the absorption resonance integrals are given for 42 elements. The method used in the work is based on the accurate measurement of the reactivity of a nuclear reactor when a sample studied is introduced into the active zone and enables the measurement of the neutron-absorption resonance integrals for reactor neutrons above the cadmium energy. For 10 elements resonance integrals not measured previously were obtained.

Reactor Characteristics

During 1955-1956 measurements of the neutron-absorption resonance integrals were carried out by the authors with the help of a heterogeneous uranium-water reactor of the "basin" type using ordinary water and enriched uranium. The critical radius of the reactor is 35 cm and its height 60 cm. The active zone contained 10 kg of U^{235}; the ratio of the number of hydrogen nuclei to those of U^{235} ~ 330. The heterogeneous reflector of the reactor consisted of natural uranium and ordinary water. The uranium rods were situated at the vertices of equilateral triangles with sides equal to 5.2 cm. The reactor was operated at a power level corresponding to a flux of thermal neutrons at the center of the active zone of 10^8 neutrons/cm^2 sec.

The cadmium ratio for gold foil, of thickness 0.05 g/cm^2, which was activated at the center of the active zone, was equal to 3.18.

The reactor was equipped with control-measurement apparatus, and devices for control, automatic regulation and accident protection.

Control was achieved by means of two pairs of boron rods. The complete extraction of one pair from the active zone, while the position of the other pair was fixed, led to an increase of the reactor power in a time τ. The reactivity ρ was determined from T, the time taken to double the reactor power which was determined by the potentiometer registering the current from a neutron chamber. The reactivity was calculated using the equation from [1]:

$$\rho = 2.6 \cdot 10^{-5}\left(\frac{54}{\tau} + \frac{20.3}{0.62+\tau} + \frac{204}{\tau+2.19} + \right.$$
$$\left. + \frac{535}{\tau+6.50} + \frac{2036}{\tau+31.7} + \frac{787}{\tau+80.3}\right),$$

where $\tau = 1.44$ T.

During the measurements the reactivity reached the value $\rho = (35\text{-}30)\cdot 10^{-5}$. Accordingly, the time taken for the reactor power to double was (162-190) sec.

The low reactor-power levels made sure that the nonlinear effects (temperature and poisoning effects) were insignificant. Changes of the atmospheric pressure did not influence the reactivity. The chosen reserve of reactivity enabled measurements on the samples studied to be made with an accuracy of $\Delta\rho = \pm 0.05 \cdot 10^{-5}$, which was determined by the accuracy with which the time for the power to double could be measured.

A cadmium pipe, with a wall thickness of $\delta = 0.5$ mm, fixed in the central cell of the reactor was used as a neutron filter; it completely stopped neutrons with an energy less than 0.49 ev [2].

Methods for Measuring the Absorption Resonance Integrals

The neutron-absorption resonance integrals were determined by a static method of measuring the reactivity of a nuclear reactor. In this method the linear dependence of the reactivity on the macroscopic cross section for the absorption of neutrons by the sample placed in the active zone was used. This phenomenon has been described in sufficient detail in [1, 3].

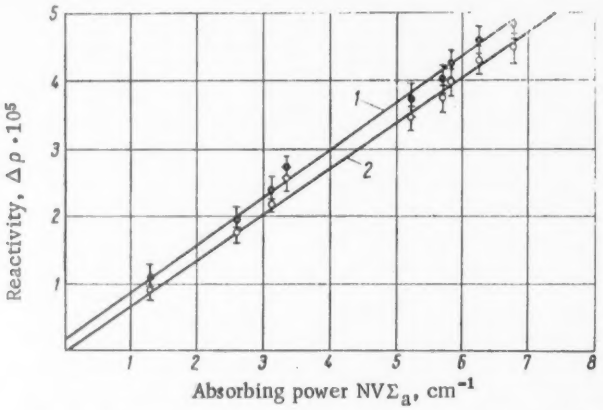

Fig. 1. Calibration lines. 1) The effectiveness of Li_2CO_3 samples, determined from the reactivity, as a function of their absorbing power without taking into account the slowing down of neutrons; 2) the same function taking into account the correction for the slowing down of neutrons $\Delta\rho_a = \Delta\rho - \Delta\rho_s$.

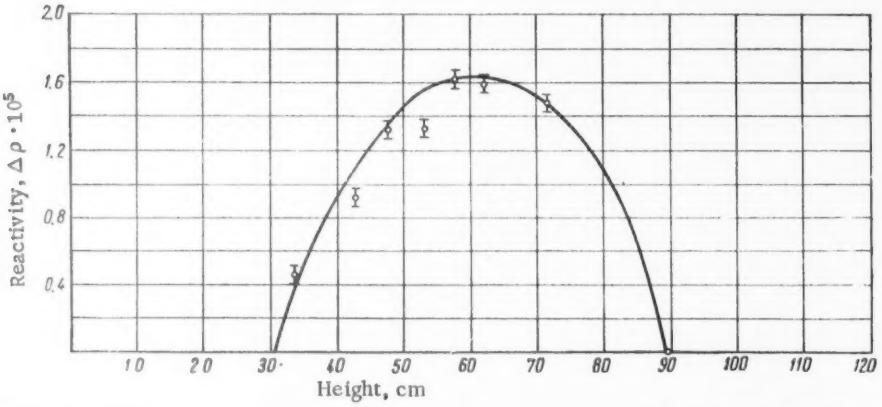

Fig. 2. The change of the reactivity when the sample is placed at different heights in the reactor ($\xi NVJ_s = 21$ cm^{-1}).

The determination of the effectiveness of the samples studied consisted of the measurement of nuclear-reactor reactivity with a standard and the sample. An empty aluminum sample container served as the standard. The difference in reactivity with the standard and with the sample $\Delta\rho = \rho_{stand.} - \rho_{sam.}$ determined the effectiveness of the sample.

TABLE 1

The Values of the Neutron-Scattering Resonance Integrals

Element	J_s, barns	References
Li	25	$J_s = \int_{0.49}^{2\cdot10^6} \sigma_s \frac{dE}{E}$, where $\sigma_s^{Li} = 1.4$ barns, $\sigma_s^{B} = 4.5$ barns [4]
B	63	
Be	70	Approximate calculation from data in [5]
F	50	Same
Cu	64	"
O	59	"
Mg	56	"
N	80	"
K	31	"
Fe	78	"
Bi	179	"
Pb	200	"
Na	51	Data of [6]
V	190	Same
Mn	425	"
Co	435	"
Br	9.2	"
Sb	36.3	"
I	53	"
W^{186}	1330	"

The results of experiments showed (Fig. 1) that the change in the reactivity of the nuclear reactor with changes of the lithium carbonate concentration in the samples takes place according to the linear law

$$\Delta\rho = BNVJ_a + C,$$

where $B = 0.684 \cdot 10^{-5}$; $C = 0.16 \cdot 10^{-5}$; N is the number of nuclei in 1 cm^3; V is the volume of the sample in cm^3 and J_a is the neutron-absorption resonance integral in barns. The difference of the constant C from zero was due to the slowing down and scattering of neutrons in the samples which led to an additional absorption of the neutrons by the cadmium.

To evaluate the role played by the slowing down of neutrons, a series of experiments were carried out in which the samples were placed at different heights in the reactor. The results of these experiments are given in Fig. 2. The experiments showed that the introduction of a graphite sample into the cadmium pipe changes the reactivity in such a way as to make the change biggest when the sample is situated at the center of the active zone.

The evaluation of the contribution to the effectiveness of the sample from the slowing down of neutrons was made experimentally. To the samples with a constant quantity of the substances investigated, was added a moderator with a small neutron-absorption cross section: graphite, beryllium oxide, magnesium oxide, sodium bismuthate or lead oxide. The geometry of the experiment was maintained unchanged. An appreciable absorption of neutrons by the filler was not observed.

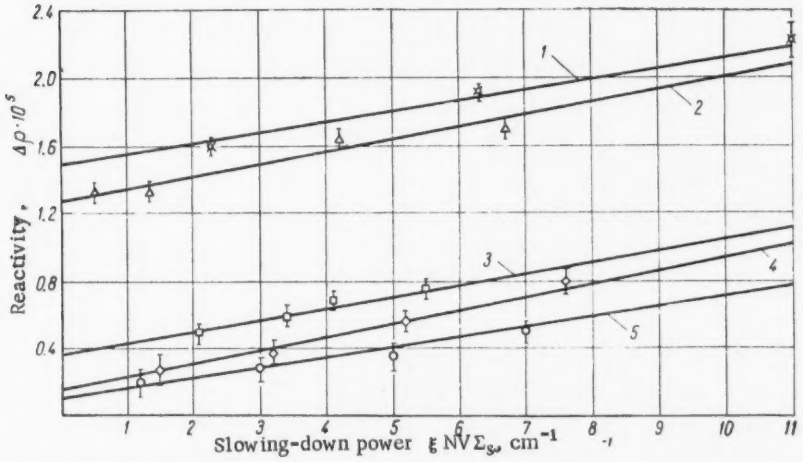

Fig. 3. The effectiveness of the samples, determined from the reactivity, as a function of their slowing-down power. The sample absorbing power NVJ_a is constant. 1) Antimony; 2) iodine; 3) strontium; 4) titanium; 5) zinc.

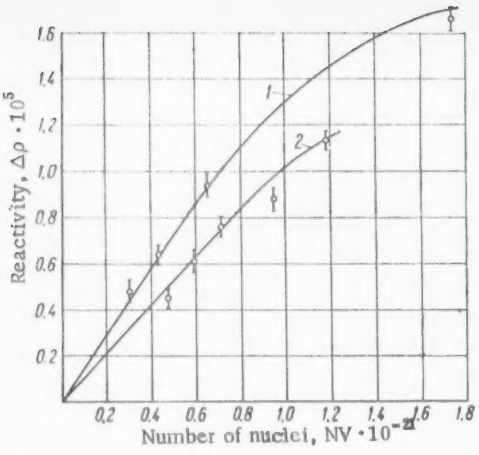

Fig. 4. The effectiveness of the samples, determined from the reactivity, as a function of the number of indium (1) and hafnium (2) nuclei.

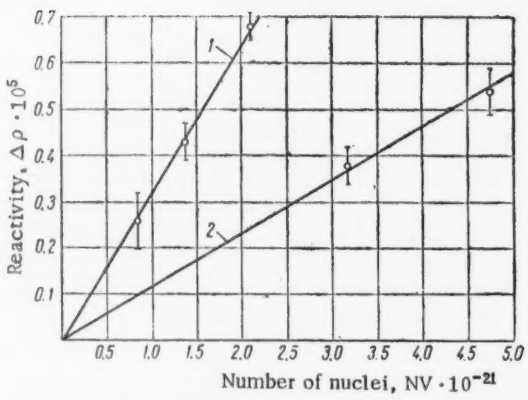

Fig. 5. The effectiveness of the samples, determined from the reactivity, as a function of the number of silver (1) and osmium (2) nuclei.

Figure 3 gives the results of measurements for antimony, iodine, strontium, titanium and zinc. From the results of these experiments it was found that the effectiveness of the samples, determined through the reactivity, depends linearly on the slowing-down power of the sample:

$$\Delta\rho = A\xi NV J_s + D,$$

where A is a constant of proportionality, $D = \Delta\rho_a$ is a term characterizing the absorbing power of the sample; ξ is the mean logarithmic energy loss of the neutrons in one collision with a nucleus of the moderator and J_s is the scattering resonance integral in barns.

The values of A and D were found by the least-squares method from all the experimental points. The coefficient A was found to be the same for all the elements investigated:

$$A = (0.070 \pm 0.030) \cdot 10^{-5}.$$

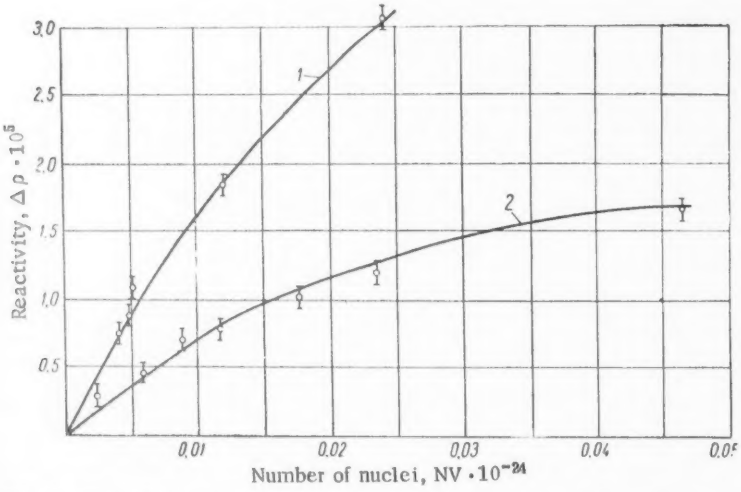

Fig. 6. The effectiveness of the samples, determined from the reactivity, as a function of the number of tungsten (1) and bromine (2) nuclei.

TABLE 2

The Values of the Neutron-Absorption Resonance Integrals

Element	Chemical compound	Value of absorption resonance integral, barns	Value of absorption resonance integral from other data, barns	References
Li	Li_2CO_3		32.2±0.6	Calculation using σ_T = (71 ± 1) barns [7]
B	$Na_2B_4O_7$	280±40	342	Calculation using σ_T = (755 ± 3) barns [7]
N	$Pb(NO_3)_2$	4.8±2.4		
F	NaF	2.3±0.5		
Cl	$BaCl_2$; KCl	12.8±1.7	12	[2]
K	K_2CO_3	3.5±1.1	1.1	[2]
Ti	TiO_2	3.8±0.9	3.0	[2]
V V^{51}	V_2O_5	3.3±0.8	 2.2	 [2]
Cr	Cr_2O_3	2.6±1.1	1.9	[2]
Mn Mn^{55}	Mn; MnO_2	11.7±1.5	10.8 11.9	[2] [2]
Fe	Fe; Fe_2O_3	2.3±0.4	2.3±0.25	[9]
Co Co^{59}	Co_2O_3	38.3±4.0 —	48 49.3	[2] [2]
Ni	Ni	3.2±0.5	4.0	[2]
Cu Cu^{65} Cu^{63}	CuO; Cu_2O	3.7±0.8	 4.4 2.2	 [2] [2]
Zn	ZnO	3.4±0.8	2.0	[2]

TABLE 2 (continued)

Element	Chemical compound	Value of absorption resonance integral, barns	Value of absorption resonance integral from other data, barns	References
Ga	Ga	11.7±2.7		
Ga^{69}			9.2	[2]
Ga^{71}			15.0	[2]
Ge	Ge	3.5±2.9		
Se	Se	9.6±1.2		
Br	NaBr	118±14		
Br^{79}			147	[2]
Rb	RbCl; $RbNO_3$	9.0±2.8		
Sr	$SrCO_3$; $Sr(NO_3)_2$	10.0±2.6	16	[2]
Zr	Zr	3.7±0.5	3	[2]
Mo	Mo; MoO_3	13.8±1.7	13,0	[2]
Ag	AgCl	466±70	650	[2]
Ag^{107}			74	[2]
Ag^{109}			1160	[2]
In	In_2O_3	2220±300		
In^{113}			1050	[2]
In^{114}			2640	[2]
Sn	Sn	5.7±0.7	4.3	[2]
Sb	Sb_2O_3	106±13		
Sb^{121}			162	[2]
Sb^{123}			138	[2]
Te	Te	50.0±6.0	36	[2]
I	I; KI	106±12	90	[2]
			130	[9]
I_{127}			140	[2]

TABLE 2 (continued)

Element	Chemical compound	Value of absorption resonance integral, barns	Value of absorption resonance integral from other data, barns	References
Cs	Cs_2CO_3	169±28		
Ba	$BaCO_3$	12.6±1.7	7.5	[2]
Ce	CeO_2	3.7±1.7		
Sm	Sm_2O_3	1790±270		
Sm^{152}			1750	[2]
Gd	Gd	67.0±8.0		
Hf	HfF_4	1470±200	1750 1300	[9] [2]
Hf^{180}			21.8	[2]
Ta	Ta_2O_5	474±62		
Ta^{181}			590	[2]
W	H_2WO_4; WO_3	290±35	170	[9]
W^{186}			355	[2]
Os	Os	180±20		
Ir	Ir	2000±490		
Ir^{191} Ir^{193}			3500 1370	[2] [2]
Hg	HgO	72.4±8	31 73	[2] [9]
Th	ThO_2	61.8±12	69.8	[2]
U U^{238}	U_3O_8; UO_2	224±40	282	[2]

The values of the scattering resonance integrals for neutrons J_s, used in the work, are given in Table 1.

The correction for slowing down is not large. For samples with a slowing-down power $\xi NVJ_s = 1$ cm^{-1} it is $\Delta\rho_s = 0.07 \cdot 10^{-5}$.

The effect of the slowing down acts additively with the absorption by the sample of neutrons with energies higher than thermal:

$$\Delta\rho = \Delta\rho_a + \Delta\rho_s.$$

The elastic scattering of neutrons by the sample placed in the center of the reactor active zone is isotropic and does not affect the reactivity.

The possible slowing down of neutrons by absorbed moisture was carefully excluded by drying the samples before the measurements were taken.

For elements having a very marked resonance absorption, it is necessary to study beforehand the dependence of the sample effectiveness on the concentration of the nuclei of the element studied and to find the linear region in which the effect of self-screening is absent. Figures 4, 5, and 6 give the results of measurements for indium, hafnium, silver, osmium, tungsten and bromine. The resonance integrals of strong absorbers can be reliably measured using a small quantity of the compounds investigated. Thus, for the measurement of the iridium and samarium integrals 50 mg of the substance is sufficient.

The absorption resonance integrals were determined relative to lithium for which the absorption cross section is well known. In the calculation of the lithium resonance integral, the absorption cross section for thermal neutrons was taken as $\sigma_T = 71.0 \pm 1.0$ barns [7].

The calibration of the system was carried out with the help of nine samples with different concentrations of lithium carbonate. After applying the method of least squares to the experimental data, taking into account the slowing down of neutrons, the following equation of the calibration line was deduced (see Fig. 1):

$$\Delta\rho_a = (0.674 \pm 0.068)\, NV J_a \cdot 10^{-5},$$

from which

$$J_a = (1.48 \pm 0.15)\, \frac{\Delta\rho_a}{NV} \cdot 10^5 \text{ barns}.$$

For the final value of the absorption resonance integral the weighted mean was taken of the values obtained for samples having different concentrations of the element investigated. Whenever possible various chemical compounds of the given element were investigated.

The accuracy of the values of the absorption resonance integrals is determined by the errors of the effectiveness of the samples and of the calibration, by the accuracy with which the slowing down of neutrons is taken into account and by the corrections for the absorption of neutrons by the other components of the chemical compound investigated. In the treatment of the experimental results the measure of reliability was taken equal to 0.7 [8].

Results of Measurement

The results of the measurement of the absorption resonance integrals are given in Table 2 where they are compared with the data of other authors.

A large part of the absorption resonance integrals obtained in the present work is in agreement with the data of other authors.

The values of the integral for cobalt, strontium and silver are somewhat smaller than the values given in [2]. The absorption resonance integral for mercury is considerably bigger than the value given in [2] but agrees with the data of [9]. The absorption resonance integrals for hafnium and iodine, on the other hand, are at variance with the data of [9] and are in agreement with the data of [2], obtained with the help of a reactor oscillator.

In determining the absorption integral for zirconium the contamination by hafnium(0.04% by weight) was taken into account.

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THE PRODUCTION OF DUCTILE NIOBIUM

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A short review is given of the properties of niobium that are of interest in connection with its use in the atomic-energy field. An account is presented of certain problems, not previously dealt with in the literature, regarding the production of ductile niobium by the sodium-thermic and carbide (carbo-thermic) methods with subsequent sintering.

A detailed description is given of the production of powder containing 98.9-99.2% niobium by the reduction of potassium fluoniobate (K_2NbF_7) with sodium and the production of ductile niobium by sintering in vacuo small bars pressed from this powder. A short description is also given of the methods of producing ductile niobium by the carbothermic process. From a study of the phase composition of the products of incomplete reduction of mixtures of niobium pentoxide and carbide, it has been established that the fundamental reaction in vacuum reduction is the sum total of the following reactions:

$$Nb_2O_5 + 5NbC \xrightarrow{< 1200^\circ C} 2NbO_2 + 5\ «NbC»\ (NbC_{0,8}) + CO,$$

where "NbC" is a phase of variable composition;

$$2NbO_2 + 5\ «NbC»\ (NbC_{0,8}) \xrightarrow{\sim 1200^\circ C} 0{,}5NbO_2 + 1.5NbO + 2.5Nb_2C + 1.5CO;$$

$$0.5NbO_2 + 1{,}5NbO + 2{,}5Nb_2C \xrightarrow{\sim 1400^\circ C} 2NbO + 2Nb_2C + Nb + 0.5CO;$$

$$2NbO + 2Nb_2C + Nb \xrightarrow{\geq 1400^\circ C} 7Nb + 2CO.$$

By special experiments it has been shown that one of the principal stages of the chosen scheme of reduction is the interaction of vapors of the lower oxides of niobium with niobium carbides. As a result of carbide reduction and sintering with simultaneous refining, ductile niobium is obtained with the following composition: ≥ 99.98% niobium plus tantalum (the latter < 0.1%), $(2.5\text{-}7)\cdot10^{-3}$% oxygen, $(3\text{-}10)\cdot10^{-3}$% carbon, $4\cdot10^{-5}$% tin, less than $1\cdot10^{-3}$% silicon, sulfur, phosphorus, copper, arsenic, calcium and magnesium, less than $1\cdot10^{-4}$% lead, bismuth, cadmium and hydrogen, < $3\cdot10^{-3}$% titanium, < $2\cdot10^{-3}$% iron and < $1\cdot10^{-5}$% antimony. The direct extraction to sintered metal is not less than 96%. It was shown that the carbide method of producing ductile niobium is the most efficient.

INTRODUCTION

In recent years niobium has found application in the atomic-energy field. It has a smaller effective capture cross section for thermal neutrons than other constructional materials except aluminum, magnesium, zirconium and beryllium, and it also possesses other valuable properties (Table 1).

Niobium does not react with liquid-metal coolants: sodium (at temperatures even above 800°C), lithium, mercury, tin, bismuth, lead (up to 800°C) and sodium-potassium alloy. Corrosion in liquid sodium at 600°C proceeds at a rate not greater than 0.025 mm/year, though it increases in the presence of oxygen dissolved in the niobium [1, 2].

TABLE 1

Physical and Mechanical Properties of Niobium

Property	Unit of measurement	Value
Atomic number	–	41
Isotopes and their abundance	Nb^{93}	(100%)
Atomic weight	–	92.91
Effective capture cross section for thermal neutrons	barns/cm^2	1.1 ± 0.1
	cm^2/g	0.0071
Crystal structure and lattice parameter	A	b.c.c.
		$a = 3.294_1 \pm 0.0003$
Density at 20°C:	g/cc	
x-ray		8.67
experimental		8.57
Coefficient of linear expansion (from 0° to 1000°C)	°C^{-1}	$7.88 \cdot 10^{-6}$
Specific heat capacity per °C	cal/g · °C	0.0647
Melting point	°C	~2500
Vapor pressure at:	mm Hg	
2194°C		$1 \cdot 10^{-5}$
2500°C		$6 \cdot 10^{-4}$
2539°C		$1 \cdot 10^{-3}$
Emissivity at λ = 6500 A	–	0.37
Thermal conductivity at:	cal/cm · sec · °C	
0°C		0.125
600°C		0.156
Specific electrical resistivity at 0°C	ohm · cm	$15.22 \cdot 10^{-6}$
Temperature coefficient of electrical resistivity at 20°C	°C^{-1}	$3.95 \cdot 10^{-3}$
Work function	ev	4.01
Ultimate tensile stress at:	kg/mm^2	
20°C		27.7
500°C		25.0
Elongation	%	49.0
Limit of proportionality at 20°C	kg/mm^2	17
Young's modulus	kg/mm^2	$8.72 \cdot 10^3$
Brinell hardness	kg/mm^2	40 and higher
Minimum creep rate at 600°C and load of 8 kg/mm^2	mm/mm/hr	$2.3 \cdot 10^{-6}$

As has been established in a number of investigations [1, 3], up to 900°C niobium interacts only slightly with uranium and hence is suitable for use as a sheathing material (can) for uranium fuel elements used in nuclear reactors involving fast and thermal neutrons [4].

It is to be noted that for canning purposes niobium of nuclear purity is used which does not contain significant amounts of oxygen and, of course, carbon and nitrogen, which on prolonged contact of niobium with uranium pass into the uranium. Thus, on contact between uranium and sheet niobium containing 0.2% oxygen, in the course of a month at 800°C the Brinell hardness of niobium falls from 200 to 90 kg/mm^2 [3].

Niobium is covered by an unusually tough and chemically passive oxide film, and hence in the cold or on a small degree of heating it is very resistant to the majority of corrosive media, excluding hydrofluoric acid and alkaline (particularly concentrated) solutions.

Additions of niobium to uranium confer on the surface of the latter a protective oxide film and at the same time stabilize the γ-phase of uranium, which increases the life of the fuel elements. Thus, an alloy with 7% niobium is satisfactorily resistant in water which does not contain free oxygen even at temperatures up to 350°C [4, 5].

TABLE 2

The Effect of Oxygen on Some Properties of Niobium at Room Temperature

Oxygen content, %	Tensile testing			Mean Vickers hardness, kg/mm²	Electrical resistivity, microhm · cm
	Tensile strength, kg/mm²	Limit of proportionality, kg/mm²	Elongation, %		
0.030	12.90	8.86	29.3	87	16.25
0.161	23.97	19.02	16.9	194	18.79
0.208	28.61	21.72	17.7	208	22.11
0.315	42,81	30.65	20.5	278	25.67
0.410	41.20	33.81	9.8	331	26.59
0.565	Brittle fracture	—	—	390	30.60

At high temperatures the film on niobium loses its protective properties and the metal becomes extremely reactive (it is used as a getter). Hence, operations that involve heating the metal above ~450°C must be carried out in a vacuum or an inert atmosphere. Niobium reacts with oxygen and carbon dioxide at high pressures and temperatures in accordance with a linear law [4].

Niobium is very ductile and can be easily cold worked under pressure by the usual methods; it can be rolled into foil without intermediate anneals, drawn into thin wire, stamped, etc., and during these processes it will work-harden less than the majority of other metals. However, with increase of oxygen, nitrogen and carbon content, the ductility of niobium rapidly deteriorates [7, 8] (see Table 2, in which are also given data on the changes in electrical resistivity).

Niobium is easily joined by resistance welding; electric welding is carried out in an atmosphere of inert gas, in water or in carbon tetrachloride.

For niobium to be used in atomic-energy applications, it must satisfy conditions of nuclear purity. Until recently methods of producing such niobium received little attention.

From papers which discuss this problem in detail, descriptions may be obtained of the development of the technology of producing ductile niobium in the laboratory [11] and on a semi-industrial scale [12] by sintering metal powder produced by the reduction of K_2NbF_7 with sodium.

Paper [7] is devoted to the properties of niobium obtained by arc melting with tungsten electrodes and the effect on them of gaseous impurities.

The carbo-thermic process of producing niobium [9], called below the carbide method, was patented in 1940. The metal is produced in accordance with the reaction

$$Nb_2O_5 + 5NbC = 7Nb + 5CO \quad (1)$$

on heating in vacuum. There is evidence [4] that at the present time the carbide method is the only method of producing niobium on an industrial scale.

In the present paper we shall review the problems of producing niobium by the sodium-thermic method [13] with subsequent sintering of the powder [14] and by the carbo-thermic method [15], which has not been adequately treated in [9, 11, 12]. They were chosen for more detailed treatment after investigation or trial of the incompletely described methods of producing niobium by reduction of Nb_2O_5 with calcium, calcium hydride and carbon [6, 9]; $NbCl_5$ or $NbCl_3$ with magnesium [10] or calcium; K_2NbF_7 or K_2NbOF_5 [6] with sodium and also by the electrolysis of melts [6]. In the majority of cases metal was obtained which was suitable for the preparation of ductile niobium by the powder-metallurgy method. However, comparison of the methods enumerated above shows that the simplest in respect of equipment and capital outlay is the sodium-thermic method [13], which was used earlier than the others for producing this metal, though the most efficient method, resulting in the production of high-quality niobium, is the carbide method [9, 10].

Sodium-Thermic Method of Producing Niobium Powder

The method of reducing potassium fluoniobate with sodium in accordance with the reaction

$$K_2NbF_7 + 5Na \rightarrow Nb + 2KF + 5NaF \quad (2)$$

and sintering the powder obtained in vacuum was developed as long ago as 1935 [16]. As a result specimens were obtained of ductile niobium. In 1939, after a method of separating tantalum and niobium had been perfected [17], a trial batch of sheet niobium was prepared.

In the development of this process optimum practices were established [13]. As raw material potassium fluoniobate was used which contained 0.01-0.04% iron, 0.16-0.21% titanium and 0.012-0.09% silicon. The charge (150 g of potassium fluoniobate and sodium 15-20% in excess of the stoichiometric requirement) was introduced into a steel reaction vessel in a series of layers. To protect the reduced metal from oxidation, the charge was covered with a layer of dry sodium chloride 15 cm thick. The vessel containing the charge was placed in a crucible furnace with Silit resistors, preheated to 600°C, and heated at 900-1000°C for 15 minutes. Reduction for a longer time or with a greater excess of sodium gave variable results. Reduction at temperatures above 1000°C was undesirable, since sodium evaporated and condensed near the surface of the protective sodium chloride layer and caught fire; there was also the possibility of the melt jumping out of the vessel. In addition, the iron content in the niobium powder was increased.

At the end of the reduction period the vessel was removed from the furnace and cooled in air. The reduced mass was easily broken up; iron was separated magnetically and the mass carefully washed with cold tap water. In this way the alkalinity of the solution was controlled and if there was a great excess of alkali it was neutralized with hydrochloric acid, since with a high content of NaOH in the solution the quality and extraction of niobium powder deteriorate (on treating niobium powder with a 1% NaOH solution (in the proportion liquid : solid = 10 : 1) for 24 hours in the cold, the niobium content decreased from 97.1 to 92.8%).

After breaking up the mass and converting it to powder, it was sifted through a 100-mesh sieve and washed with hot water until fluorine ions had been eliminated, since the presence of the latter leads to losses of niobium owing to solution during subsequent treatment of the powder with nitric or hydrochloric acid.

Powder with the highest content of niobium (99.3%) was obtained by washing with cold 10% nitric or 5% hydrochloric acid for 3 hours (in the proportion liquid : solid = 10 : 1) with a subsequent 15-minute treatment with 2.5% hydrofluoric acid. The use of hydrofluoric acid reduces the oxygen content in the powder, as it dissolves the surface oxides on the niobium more rapidly than it does the metal.

By washing the mass with distilled water it is possible, omitting the treatment with hydrochloric or nitric acid and continuing the washing in the cold for an hour while mixing with 1% hydrofluoric acid (with a ratio of solid : liquid = 1 : 10), to obtain metal suitable for sintering and containing 99.0% niobium, 0.03% silicon and < 0.01% calcium.

It was observed that iron from the potassium fluoniobate passed almost entirely into the metal, thereby reducing the degree of purification of titanium, while iron entering the mass from the reaction vessel can be partly removed magnetically and satisfactorily washed out with acid, so that titanium can be reduced to 0.02-0.06%.

After washing with acid the powder is washed with water and then dried. The quality of the powder undergoes hardly any change on heating to 120°C. At 150°C the niobium powder begins to oxidize in air. The content of niobium, reaching 99.3%, was determined from the increase in weight of a specimen of powder on heating in air at 800°C. The accuracy of the determination, making corrections for the content of titanium, iron and silicon, was $\sim \pm 0.1\%$.

By reducing, in accordance with the procedure described, larger charges of potassium fluoniobate, powder was obtained with a size -100 mesh; a typical composition for it is given in Table 3; the direct extraction of niobium > 90%. The powder is entirely suitable for the production of ductile niobium by the powder-metallurgy method.

It may be noted that niobium powder can also be obtained by similar procedures from potassium oxyfluoniobate after completely removing its water molecules by drying at 200°C [6, 18].

The Production of Compact Ductile Niobium from Powder [14, 19]

The production of pure ductile niobium from metal powder is attended by a number of difficulties, connected mainly with its high melting point and great reactivity on heating. The metal is obtained by compressing the powder into small bars and sintering them in vacuo.

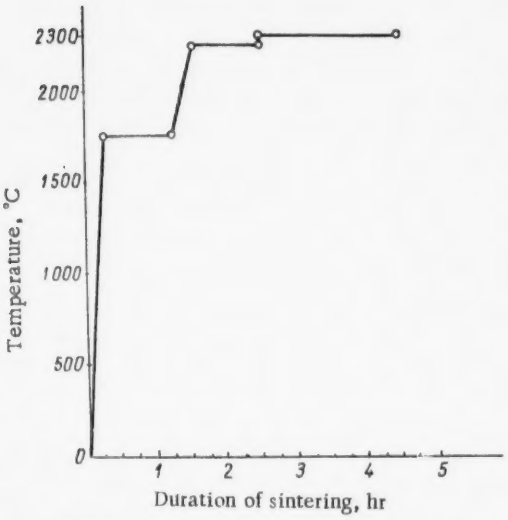

Fig. 1. Scheme for sintering small niobium bars 10 ×10 × (70-140) mm.

To determine the optimum conditions of pressing and sintering, a niobium powder was used which contained 98.3% niobium, 0.35% tantalum, 0.06% titanium, 0.07% iron, 0.14% silicon, 0.04% lead, 0.26% carbon, ~ 0.5% oxygen and 0.07% nitrogen. It was moistened with a solution of paraffin in benzene or with benzene and compressed in a hydraulic press with a split steel die into small bars of dimensions 10 ×10 × (70-140) mm. It was found that by increasing the compacting pressure the porosity and specific electrical resistivity of the compressed bars (from which the lubricant had previously been eliminated) decrease, while the contact surface increases. However, the porosity of the bars after sintering in accordance with a particular procedure varies only within narrow limits. Compacting under a pressure of 2.6 tons/cm^2 and more led to distortion of the bars during sintering and to the formation of cavities, and hence the compacting pressure was limited to 1-1.5 tons/cm^2.

The sintering of niobium is a very complex process of forming compact metal from powder, accompanied by grain growth and simultaneous refining of the metal by volatilization of the impurities. Efficient sintering practice must ensure refining of the metal, so that a high density is obtained and the intercommunicating pores are closed up; otherwise, as a result of the increase in pressure of the gases and impurity vapors given off in the closed pores, large pores may form and swelling take place within the bars. Hence, the correct choice of sintering temperature schedule and the impurity content in the raw material plays a large part.

Experiments have shown that no substantial removal of iron, titanium and silicon takes place during the sintering process; this is explained by the high density of the metal and by the formation of closed porosity at the temperatures at which refining would be possible. No positive results were obtained from attempts to increase the porosity of the sintered metal by reducing the compacting pressure, by preliminary heating of the powders with the object of lowering the excess of free energy of the crystallites, by sintering fractions of powder of various grain sizes or by introducing into the composition of the charge materials which volatilize during sintering and make compacting more difficult. Bars having a porosity of ~ 30% could be obtained only from coarse-grained niobium hydride powder. Hence, not more than 0.1% iron and 0.1% silicon are permitted in the initial powder, with not less than 98.6% niobium, and an increase of weight in the powder during heating in air of not less than 41.7-42.0%.

Investigations have shown [19] that to increase the rate of sintering in a vacuum of the order of $5 \cdot 10^{-3}$ mm Hg and to obtain high ductility metal, it is desirable for the sintering to take place in one stage in accordance with the schedule shown graphically in Fig. 1, in contradistinction to the two-stage procedure [11]. The first, small, holding period during the heating of the bars must take place at a temperature not lower than 1750-1780°C. The second, longer, holding period must be at a maximum temperature of 2250-2350°C. Between these periods a rapid rise in temperature is permissible (and up to 1750°C it is essential if a high vacuum is not used).

Sintering niobium bars of average size in a vacuum of $5 \cdot 10^{-3}$ - $5 \cdot 10^{-4}$ mm Hg in accordance with the practice depicted in Fig. 1 takes 4.5-5 hours and results in the production of soft ductile metal containing ~ 99.5% niobium and tantalum which is easily cold worked. After cold forging to a reduction of 50% and annealing (second sintering) at 2250°C, the density of the metal increases to 8.3-8.4 g/cc. The metal can be readily rolled into strip and foil and drawn into wire.

TABLE 3

Characteristics of the Metal Powder and of the Metal Obtained from It

Product	Composition, wt.%											Characteristic of structure
	Nb+Ta	Ti	Fe	Si	Pb	C	O	N	S	P	Cd	
Powder produced by the sodium-thermic process	98.9—99.2	0.02—0.06	0.04—0.07	0.03—0.06	0.1—0.3	0.09—0.15	~0.5	to 0.1	$3 \cdot 10^{-3}$	~0.01	—	Grain size <2.5 μ - 38% ~2.5 μ - 34% ~5.0 μ - 28%
Compact sintered metal	99.4—99.5	~0.03	~0.05	0.05	$< 1 \cdot 10^{-4}$	~0.01	~0.03	~0.03	$2 \cdot 10^{-3}$	<0.01	$1 \cdot 10^{-4}$	7.8—8.0 g/cm³

In compacting bars of cross section 20 × 20 mm, the niobium powder is moistened with benzene in the proportion of 100 ml of benzene to 2300 g of powder. The compacting pressure for the powder is 1.0-1.5 tons per cm^2, and for a mixture of the powder with 25 weight% hydride 2.5-3.5 tons/cm^2. The time at the maximum sintering temperature of 2250°C is 6 hours. The whole sintering process occupies 8 hours and is carried out in a vacuum not lower than $1 \cdot 10^{-2}$ mm Hg. The characteristics of the sintered metal are given in Table 3. The second sintering of niobium sheets cold worked to a reduction of 50% is carried out at a temperature of 2200-2150°C. Such a high temperature is required not for annealing (the recrystallization temperature is 1200°C), but for welding up the compressed micropores. The Brinell hardness values of the bars after sintering, working and sintering a second time are 60-70, 100-130 and 60-80 kg/mm^2, respectively.

Niobium sheets after the second sintering have a density of 8.53 g/cc, a limit of proportionality of 25.5-29.7 kg/mm^2, a yield point of 29.5-34.0 kg/mm^2, an ultimate tensile strength of 39.4-43.2 kg/mm^2 and an elongation of 10.0-18.1%. During rolling the sheets can undergo a reduction of 99.8% without intermediate annealing. Strip or foil of thickness down to 20 microns can, after annealing, be rolled into foil 12-14 microns thick.

Compact niobium can also be subjected to other forms of working under pressure, for example, for the production of wire or seamless tubes.

Carbide (Carbo-Thermic) Method of Producing Niobium

In this method of producing niobium it is possible to use as raw material pentoxide or niobium carbide obtained by the treatment of ore concentrate.

If niobium carbide is used as raw material, part of it is converted into niobium pentoxide by heating in air. However, as a rule niobium pentoxide is used as raw material. In this case > 72% of it is converted into carbide by heating with an admixture of carbon black at 1800°C in a stream of hydrogen in a continuous tubular furnace. A slightly sintered mass of carbide is obtained which is easily broken up into a powder of 80 mesh.

Detailed studies of the carbide method of producing niobium [15] have shown that accurate weighing of the components of the charge in accordance with Reaction (1) is not necessary, and it is permissible to have up to 10% excess Nb_2O_5, which is removed in the form of lower oxides of niobium. To obtain metal with a minimum content of carbon impurity, a charge is prepared which has 5% Nb_2O_5 in excess of the stoichiometric amount.

The carbon content and porosity of the metallic niobium obtained depend on the size of the initial niobium carbide powder. The sintered metal obtained by using a fraction of carbide powder of size −100 + 200 or carbide powder of size −60 or −100 mesh contains the minimum amount of carbon. In the latter case the porosity amounts to 8-9%, and the material is suitable for the production (after working and high-temperature annealing) of high-quality ductile metal.

The density of the sintered niobium also depends to a considerable extent on the time of mixing of the niobium pentoxide and carbide (the average weight of the mixture as poured = 1.45 g/cc; the weight as shaken down = 2.2 g/cc). By varying the time of mixing it is possible by reduction and sintering to obtain metal with a predetermined porosity within the limits 5-38%.

The porosity and carbon content of the sintered metal are affected by the pressure used in compacting the mixture of niobium pentoxide and carbide. The optimum specific compacting pressure is 1 ton/cm^2.

Experiments on the reduction of the mixture were carried out in vacuo in an electric furnace with graphite heaters. The reduction reaction proceeds at a considerable rate even at 1400°C and is complete and rapid enough at 1700°C. After holding for 3 hours at this temperature, 97.4% had reacted and metal containing 99.2% niobium and 0.25% carbon was obtained; the whole process took about 4 hours. The bars lost 17.7% in weight on account of the formation of CO and 3.2% on account of the evaporation of impurities and lower oxides of niobium and mechanical losses.

During the period of most active reduction the gas pressure rose from $1 \cdot 10^{-2}$ to 0.1-0.3 mm Hg and then fell again to $(1\text{-}2) \cdot 10^{-2}$ mm Hg.

In accordance with the principle of successive transformations during the reduction of oxides [20], the overall reduction reaction (1) at high temperatures in vacuo can be represented as a series of successive reactions:

$$Nb_2O_5 + 5NbC \xrightarrow{< 1200^\circ C} 2NbO_2 + 5\,«NbC»\,(NbC_{0.8})^* + \uparrow CO, \quad (3)$$

$$2NbO_2 + 5\,«NbC»\,(NbC_{0.8}) \xrightarrow{< 1200^\circ C} \rightarrow 0.5\,NbO_2 + 1.5\,NbO + 2.5\,Nb_2C + \uparrow 1.5CO, \quad (4)$$

$$0.5NbO_2 + 1.5\,NbO + 2.5\,Nb_2C \xrightarrow{< 1400^\circ C} \rightarrow 2NbO + 2Nb_2C + Nb + \uparrow 0.5CO. \quad (5)$$

$$2NbO + 2Nb_2C + Nb \xrightarrow{> 1400^\circ C} 7Nb + \uparrow 2CO. \quad (6)$$

This representation of the chemistry of the process was confirmed by the results of x-ray structure analysis of the intermediate products of the reduction reaction (Table 4).

With the object of throwing light on the fundamental features of the mechanism of the process, determinations were also made of such properties of the individual phases as the melting point, volatility and tendency to disproportionate during heating. From qualitative experiments it has been possible to determine that NbO_2 does not melt even at 1850°C, while NbO melts around 1900°C, both having considerable volatility at 1700°C and very marked volatility at 1850°C. In a vacuum of $1 \cdot 10^{-3}$ - $5 \cdot 10^{-4}$ mm Hg the dissociation of NbO_2 (according to the x-ray data) is imperceptible at 1850°C, and that of NbO at the melting point.

* The phase "NbC" is homogeneous within the limits from NbC to $NbC_{0.72}$.

TABLE 4

Phase Composition of the Products of Reduction of Niobium Oxides by Niobium Carbide

Conditions of reduction		Degree of reduction of niobium, %	Phase composition of the product of reduction*
Temperature, °C	Time, hrs		
1200	24	29.3	NbO_2, NbO, NbC
1400	3	47.5	NbO, Nb_2C, NbC, small quantity of NbO_2
1400	6	62.0	NbO, Nb_2C, small quantity of metallic niobium
1400	9	64.8	The same phases
1400	12	84.3	The same phases but present in equal quantities
1700	3	97.4	Metallic niobium; very small quantities of NbO and Nb_2C
2300	3	~100	Metallic niobium (a = 3.300 A)

* Determined by A. S. Znamenskii

TABLE 5

Chemical Composition of Initial Niobium Pentoxide and of Sintered Metal Produced by the Carbide Process

Name of element	Content, %		Sensitivity of method of analysis, %
	Initial niobium pentoxide	Metal	
Niobium + tantalum*	–	99.983-99.994**	–
Titanium	0.5***	Not detected	$3 \cdot 10^{-3}$
Iron	–	The same	$2 \cdot 10^{-3}$
Silicon	0.5	"	$1 \cdot 10^{-3}$
Sulfur	0.5	"	$1 \cdot 10^{-3}$
Phosphorus	0.1	"	$1 \cdot 10^{-3}$
Tin	0.07	$4 \cdot 10^{-5}$	–
Lead	0.24	Not detected	$1 \cdot 10^{-4}$
Antimony	> 0.1	The same	$1 \cdot 10^{-6}$
Bismuth	> 0.1	"	$1 \cdot 10^{-4}$
Cadmium	> 0.1	"	$1 \cdot 10^{-4}$
Arsenic	–	"	$1 \cdot 10^{-3}$
Calcium	–	"	$1 \cdot 10^{-3}$
Magnesium	–	"	$1 \cdot 10^{-3}$
Hydrogen	–	"	$1 \cdot 10^{-4}$
Oxygen	–	$(2.5\text{-}7) \cdot 10^{-3}$	–
Carbon	–	$(3\text{-}10) \cdot 10^{-3}$	–
Copper	–	Not detected	$1 \cdot 10^{-3}$

* The content of tantalum is determined from the ratio Ta/Nb in the initial niobium pentoxide; usually it is less than 0.1%.

** Determined by difference.

*** In the case of a higher titanium content (up to 3-4%) and also the majority of other impurities, pure niobium can be obtained by a somewhat different sintering procedure.

Niobium carbides, which are phases of variable composition, are characterized by extremely high melting points (> 3500°C) and by low vapor pressures; their dissociation at the temperature of reduction of the oxides is negligibly small. In addition special experiments were carried out to determine the part played by the gaseous phase in the chosen reduction procedure.

A briquette of NbC powder was placed at a distance of 3-4 mm from a briquette of NbO_2 of NbO powder. On heating them to 1700-1850°C in a vacuum of $(5\text{-}10)\cdot10^{-4}$ mm Hg, the niobium oxide vapors spread to the carbide briquette and were reduced on it. A layer of metal (a = 3.301 A) appeared on the surface of the carbide and under it a layer of lower carbide. With rise of temperature the thickness of these layers rapidly increased. If a briquette of lamp black was placed above a NbO briquette, then a layer of metal with a somewhat increased lattice parameter (a = 3.310 A) also formed on the lamp black, though scarcely touching it. These experiments, carried out under conditions resembling closely those of the actual reduction process, show that one of the most important stages of the mechanism of carbo-thermic reduction is the interaction of vapors of lower niobium oxides with solid niobium carbides.

Such a picture of the reduction explains also the high rate of the process and the effect on it of various technological factors.

In order to lay down more precisely the sintering practice and maximum temperature, niobium bars, after reduction by holding for 3 hours at 1700°C, were heated in vacuo by passing an electric current through them at temperatures of 2330, 2390, 2450, or 2470°C. The metal melted at a temperature around 2490°C. In the remaining cases bars of ductile metal were obtained. After forging and annealing (second sintering) at 2200°C, it was cold rolled into strips 0.1 mm thick.

Fig. 2. Structure of niobium after forging and second sintering. Produced by the carbide process (×200).

By vacuum sintering for 3 hours at 2350°C bars of metal reduced at 1400-1800°C, it was found that the niobium and carbon contents of the sintered metal depended little on the composition of the reduction product.

At the beginning of the sintering process the gas pressure rose for short periods from $5\cdot10^{-3}$ to $5\cdot10^{-2}$ mm Hg, then fell and sintering proper proceeded in a vacuum of $5\cdot10^{-3}$ and $5\cdot10^{-4}$ mm Hg. Experiments showed that if a considerable deterioration of the vacuum could be tolerated during reduction, then sintering had to be carried out in the highest possible vacuum.

Increasing the holding time at 2350°C from 1 to 6 hours had practically no effect on the niobium and carbon contents in the metal; with increase of the holding from 1 to 3 hours, the oxygen content decreased from 0.051 to 0.0025%. Table 5 shows the impurity content in the sintered metal as compared with the content in the initial niobium pentoxide. From this it can be seen that in the process of carbide reduction and subsequent vacuum sintering refining of the metal proceeds considerably more actively than during the sintering of niobium powder. This is explained by the presence of considerable intercommunicating porosity and by the existence in the initial charge of oxygen which facilitates the removal of impurities in the form of oxides which are more volatile than the pure metals. Direct extraction into sintered metal was not less than 96%.

After forging and high-temperature annealing (second sintering), niobium has a Brinnell hardness of about 80 kg/mm^2 and a structure (Fig. 2) suitable for cold rolling without annealing into stip and foil down to 20 microns thick, and for other forms of working under pressure.

From the investigations carried out it may be concluded that the fundamental technological and economic advantages of the carbide method of producing niobium are as follows: a) the use of commercial niobium pentoxide as raw material and of a cheap reducing agent (carbon); b) the formation as a result of reduction of com-

pact metal suitable for sintering and arc melting; c) the relatively short duration of the processes of reduction and subsequent sintering; d) the high direct extraction of niobium; e) the possibility of producing high-purity ductile niobium even when using as raw material niobium pentoxide contaminated by impurities.

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ON THE MODES OF OCCURRENCE OF URANIUM IN ROCKS

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The question of the modes of occurrence of uranium in rocks is extremely important in explaining the conditions under which ore deposits are formed. This was first made clear by V. I. Vernadskii. Widespread studies in recent years, made by Soviet and foreign scientists, have supported the suggestions of V. I. Vernadskii and have defined the modes of occurrence of uranium in rocks more precisely: 1) uranium minerals; 2) isomorphous admixtures of uranium in the crystal lattice of nonuranium minerals; 3) uranium in a dispersed state, adsorbed by minerals and rocks and dissolved in water in rocks.

The modes of occurrence of uranium in nature was first examined by V. I. Vernadskii in 1910 [1]. He wrote, "Uranium minerals do not contain all the uranium in the earth's crust. In addition to its occurrence in special minerals, uranium enters an entire series of other bodies as admixtures . . . these admixtures, containing uranium, may hold it by combining with it, in which case they are either mechanical, microscopically small, inclusions of uranium minerals or they are solutions of uranium combinations. But there are occurrences where uranium is dispersed in other bodies under special conditions, not perceptibly entering into combination." In 1934 V. I. Vernadskii [2] again returned to the question remarking that uranium "is exposed everywhere about us; it is disseminated not only in rocks, but is found in all the minerals as well." At the same time he emphasized that "in rocks containing a quantity of uranium attaining $4.7 \cdot 10^{-3}$ % and more, no primary uranium minerals are known . . . No less characteristic is the fact that it is not found in isomorphous mixtures with the rock-forming minerals. Only sometimes, apparently, is it encountered in such minerals, and those are rich in thorium – in monazite, xenotime, thorianite . . . in larger quantities than is disseminated in rocks, but these concentrations cannot explain its occurrence in such quantities as disseminations in igneous rocks. We must therefore propose that it is found there in forms not bound in chemical combinations, that it is there disseminated in atoms more or less free, pervading all earth material, or dissolved in capillary water in rocks."

Consequently, V. I. Vernadskii considered that uranium in rocks a) forms uranium minerals, b) enters isomorphously into the lattice of nonuranium minerals, and c) occurs in disseminated states as atoms or solutions in water in rocks.

The content of uranium in the earth's crust and in the rocks where it occurs, according to the data of A. P. Vinogradov [3], follows:

a) Earth's crust	$3 \cdot 10^{-4}$%
b) Magmatic rocks:	
Ultrabasic rocks (dunite, peridotite, pyroxenite)	$3 \cdot 10^{-6}$%
Basic rocks (basalt, gabbro, diabase)	$3 \cdot 10^{-5}$%
Intermediate rocks (diorite and andesite)	$1.8 \cdot 10^{-4}$%
Acid rocks (granite, liparite, rhyolite, etc.)	$3.5 \cdot 10^{-4}$%
c) Sedimentary rocks:	
Clay and shale	$3.2 \cdot 10^{-4}$%

TABLE 1

Distribution of Uranium in Minerals in the Granite Chernovo Massif, Altai Mountains [4] (in %)

Mineral	Biotite granite			Two-mica granite		
	Content of mineral in the rock	Content of uranium in the mineral	% uranium occurring in the given mineral	Content of mineral in the rock	Content of uranium in the mineral	% uranium occurring in the given mineral
Quartz	34	$7 \cdot 10^{-4}$	11	38.5	$9 \cdot 10^{-4}$	17.5
Plagioclase	43	$1 \cdot 10^{-3}$	19.5	40.5	$1 \cdot 10^{-3}$	20.5
Microcline	20	$8 \cdot 10^{-3}$	7.3	17	$1 \cdot 10^{-3}$	8.5
Biotite	1.8	$1 \cdot 10^{-2}$	8.2	—	—	—
Mica (biotite and muscovite)	—	—	—	1.7	$1.5 \cdot 10^{-2}$	13.0
Magnetite	0.9	$1 \cdot 10^{-2}$	4.1	0.7	$3 \cdot 10^{-2}$	10.5
Electromagnetic fraction (monazite, zircon, delorenzite, and others)	0.35	$3 \cdot 10^{-1}$	47.7	0.19	$4 \cdot 10^{-1}$	38
Nonelectromagnetic fraction (fluorite, apatite, and others)	0.1	$5 \cdot 10^{-3}$	0.5	0.25	$1 \cdot 10^{-2}$	1
Total	—	—	98.3	—	—	109.0

The above cited data show that the highest content of uranium is in acid rocks where it sometimes attains $3 \cdot 10^{-3}$%. For example, in the granites of the Chernovo massif (Altai Mountains), according to L. V. Tauson [4], it ranges from 1.2 to $3 \cdot 10^{-3}$%. Inasmuch as uranium minerals are generally absent in magmatic rocks, the question of their mode of occurrence presents considerable interest.

During recent years a great number of investigations have been made in this direction in consequence of which the question has been defined more precisely, but nothing fundamentally new has been introduced to the ideas of V. I. Vernadskii. Thus according to data from American investigators [5], uranium occurs in igneous rocks in six forms: 1) it forms uranium minerals; 2) it enters into rock-forming minerals isomorphically; 3) it is held in composition by cation exchange; 4) it is adsorbed on the surfaces of crystals and grains; 5) it is in a dissolved state in liquid inclusions within rock-forming minerals; and 6) it is found in solution in intergranular fluids.

Studies by Soviet [4] and foreign [6] scientists have shown that the highest concentration of uranium in minerals in magmatic acidic rocks is encountered in the dark and accessory minerals (amphibole, biotite, pyroxene, monazite, sphene, apatite, and others). But from 35 to 70% of the total quantity of uranium occurring in the rocks (Tables 1 and 2) is found in the quartz-feldspathic parts of the granitoid rocks.

During formation of the magmatic rocks uranium is distributed in them in various forms depending on the geological and physicochemical conditions. For example, if the magma crystallizes without loss of the volatile constituents, then the rocks forming from it contain all the uranium having occurred in the magma; but on the other hand, with considerable loss of volatiles the larger part of the uranium may be carried away from the magma and only a small part of the uranium present in the magma may remain in the intrusive rock.

In the molten masses out of which magmatic rocks are formed, the content of uranium is not great; therefore, conditions for the concentration of uranium as independent uranium minerals are unfavorable in the majority of cases; consequently, they are not generally observed. Only ocassionally are primary uranium minerals encountered, for example, brannerite, a metatitanate of uranium, thorium, and rare earth elements (U, Y, Th, Ca, Fe)Ti_5O_{16}, having in its composition 8.87-29.9% UO_2 and 11.4-43.3% UO_3 (nearly 36-44% uranium). There are individual indications of the occurrence in magmatic rocks of minerals of the group of complex oxides (tantalate-niobates) containing uranium (euxenite and others), and also uraninite.

It is possible that primary uranium minerals (brannerite, uraninite, and others) occur in magmatic rocks in the form of submicroscopic segregations indeterminable by means of the polarizing microscope.

TABLE 2

The Content of Uranium in Minerals of the Conway Granite, New Hampshire (USA) [6] (in %)

Mineral	Biotite granite		Amphibole granite	
	From-to	average	From-to	average
Feldspar	$2.0 \cdot 10^{-4}$—$5.3 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$—$2.2 \cdot 10^{-4}$	$1.8 \cdot 10^{-4}$
Quartz	—	$2.3 \cdot 10^{-4}$	—	$5.0 \cdot 10^{-4}$
Magnetite	$0.8 \cdot 10^{-5}$—$3.2 \cdot 10^{-3}$	$1.58 \cdot 10^{-3}$	$1.0 \cdot 10^{-4}$—$2.57 \cdot 10^{-3}$	$9.6 \cdot 10^{-4}$
Amphibole	$1.6 \cdot 10^{-3}$—$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$	$1.0 \cdot 10^{-4}$—$4.88 \cdot 10^{-3}$	$2.04 \cdot 10^{-3}$
Fluorite	—	$1.4 \cdot 10^{-3}$	—	$6.30 \cdot 10^{-3}$
Biotite	—	$3.8 \cdot 10^{-3}$	—	$1.97 \cdot 10^{-3}$
Ilmenite	$4.7 \cdot 10^{-3}$—$5.0 \cdot 10^{-3}$	$4.85 \cdot 10^{-3}$	—	$9.8 \cdot 10^{-4}$
Zircon	$2.52 \cdot 10^{-2}$—$1.75 \cdot 10^{-1}$	$1.202 \cdot 10^{-1}$	$7.55 \cdot 10^{-2}$—$2.35 \cdot 10^{-1}$	$1.249 \cdot 10^{-1}$
Allanite	$5.4 \cdot 10^{-2}$—$6.56 \cdot 10^{-2}$	$6.17 \cdot 10^{-2}$	—	$7.85 \cdot 10^{-2}$
Content of uranium in the granite	$3.9 \cdot 10^{-4}$—$1.82 \cdot 10^{-3}$	$1.18 \cdot 10^{-3}$	$7.2 \cdot 10^{-4}$—$1.16 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$

The second rather widespread mode of occurrence of uranium in rocks is that in which uranium enters by isomorphous substitution many accesory minerals (monazite, xenotime, orthite, thorite, and others). In addition, uranium occurs in magmatic rocks in a dispersed state; in an adsorbed form on the surfaces of crystals and grains of minerals (ionic adsorption) or in a dissolved state in liquid inclusions and intergranular fluids. The suggestion of V. I. Vernadskii that uranium occurs in rocks in a dispersed state as atoms is improbable because of the element's high chemical activity and, in particular, because of its great affinity for oxygen.

The determination of the quantitative relationships among the various modes of occurrence of uranium in magmatic rocks has many practical difficulties at present. All that it is possible to conjecture is that the principal mass of uranium in magmatic rocks is bound up with uranium minerals of submicroscopic size and with minerals in which uranium enters by isomorphous substitution. It occurs in an adsorbed form in small quantities and in still smaller quantities in a dissolved state in liquid inclusions and in intergranular fluids.

The general content of uranium in magmatic rocks and the quantitative relations among the separate modes of occurrence are determined by the conditions of formation of the rock and by its history following that event. They are commonly not identical to the primary uranium content in the magma and are changed after the rock is formed by post-magmatic processes of mineral formation and metamorphism, and also by weathering processes.

In magmatic rocks a significant part of the uranium is found in combinations easily dissolved by weak acids or by other specific solvents (for example, by carbon dioxide and ammonia, as studies by L. V. Tauson show). The extraction of uranium by this process, without destroying the rock-forming minerals, may amount to 90%.

The sources of easily leached uranium may be:

1. Primary uranium minerals belonging to the oxides (uraninite, pitchblende) and to the complex oxides (brannerite and others), to the extent that besides quadrivalent they also have hexavalent uranium, which is easily dissolved in weak acids. The primary minerals of uranium, especially the oxides uraninite and pitchblende are easily replaced in the zone of oxidation by secondary minerals – silicate, sulfates, carbonates, phosphates, arsenates, vanadates, etc., in which uranium is hexavalent (in the form of the uranyl group). All secondary minerals of uranium are also easily dissolved by weak acids.

2. The nonuranium minerals, in which uranium occurs as isomorphous admixtures (zircon and its variations, orthite, monazite, thorite, etc.), if they are observed in a metamict state [7].

3. Adsorbed uranium.

4. Uranium occurring in solution in liquid inclusions and in intergranular fluids.

Uranium easily leached from rocks, and commonly called "lixivial," "free," or "labile," L. V. Tauson [4] proposed to call "nonisomorphous modes of occurrence of uranium." This latter term is also unfortunate inasmuch as the source of easily extracted uranium from rocks may have been minerals also containing hexavalent uranium, as was noted above.

Easily extracted uranium may be carried out of rocks composing the earth's crust by post-magmatic pneumatolitic-hydrothermal solutions or by ground water and again deposited at another locality sometimes with the development of economic concentration. The quantity of uranium carried out of these or other rocks is determined in the first place by the composition of the rock and by the degree of its decomposition, the mode of occurrence of uranium in the rock, and the composition of the solutions passing through the rock.

The study of magmatic rocks with the aim of determining the total content of uranium in them and the uranium easily extracted from the rock undoubtedly is very important inasmuch as it aids in showing the genetic connection of the origin of the uranium with the magmatism of a definite intrusion and in directing the search for signs of potential ore-bearing intrusions in regions where one may expect to discover economic deposits of uranium.

On this question G. J. Neuerburg [5] wrote, "It may be supposed that exceptionally small quantities and low proportions of labile uranium may identify some rocks that were a source of uranium, possibly deposited elsewhere in economic amounts."

Another suggestion, opposed to the opinion of Neuerburg, is more probable, namely, that deposits of uranium are necessarily connected with the rocks in which there are not small but large quantities of highly labile uranium.

The mode of occurrence of uranium in sedimentary and metamorphic rocks is similar to that originating in magmatic rocks.

Uranium occurs in them fundamentally in the adsorbed state and as mineral oxides (uraninite, pitchblende, and coffinite) and of uranium-organic combinations. These latter have been studied by no one up till now. Also a few parts of uranium may possibly be connected with isomorphous substitution for other cations, for example, calcium in phosphorites.

Increased concentrations of uranium in sedimentary and metamorphic rocks is commonly observed in those varieties which contain organic substances. Deposits of uranium have been identified in marine carbon-containing black shales, in coal and carbonaceous shales, in limestones and sandstones with organic substances, and also in marine phosphorites.

It has been suggested that organic substances may 1) restore uranium to the quadrivalent state with the formation of oxides of uranium (uraninite and pitchblende); 2) absorb uranium; 3) form insoluble combinations with uranium. According to some authors [8] these are probably uranyl-humate complexes, but according to others [9], they are urano-organic complex combinations in the form of humates, sulfates, and melanoidal uranyl.

In phosphorites uranium is concentrated as a result of chemical adsorption (apparently as co-precipitate) or as isomorphous substitution by uranium of calcium in phosphoritic substances [10]. The conduction of recent studies of apatite, which has been separated from uraniferous phosphorite, has indicated that it contains a significant quantity of uranium (2.39% UO_2), which enters into the crystalline lattice of apatite [11].

Uranium in the zone of oxidation, having formed in the process of weathering from sedimentary and metamorphic rocks as well as from magmatic, generally occurs in the form of uranium minerals, extremely variable in composition (autunite, torbernite, tyuyamunite, carnotite, uranophane, kasolite, etc.) or in an adsorbed form chiefly in opal and iron hydroxides.

CONCLUSIONS

Uranium is encountered in various forms in rocks:

1) It forms uranium minerals of various compositions (oxides, hydroxides, sulfates, carbonates, silicates, phosphates, arsenates, vanadates, etc.);

2) as a result of isomorphous substitution it enters into the crystal lattice of nonuranium minerals;

3) it occurs in a dispersed state – a) in an adsorbed form in minerals and rocks (ionic form of adsorption) and b) in a state of solution in water in rocks.

After the formation of the rocks which compose the earth's crust, a change in the total content and distribution of uranium among the various modes of occurrence in rocks took place. Therefore, the total content of uranium and the quantitative relations among the various modes of its occurrence in rocks are determined not only by the conditions of formation of the rock but by its subsequent history.

Further study is necessary on the modes of occurrence of uranium and its quantitative relationships in rocks of various origins – magmatic, sedimentary, and metamorphic – to the end of explaining the conditions favorable to the concentration of uranium in one or the other of its forms and the determination of the genetic connection of the origin of uranium deposits with magmatism or processes of sedimentary accumulation(for deposits of sedimentary origin). In addition to this, special heed needs to be paid to the determination of signs of potential uranium ore-bearing intrusions. In the first place it is necessary to decide the question whether a lower or a higher content of highly labile uranium in magmatic rocks serves as a sign which indicates that these rocks are sources of uranium ore deposits. The most probable of all these signs is perhaps the high content of uranium in magmatic rocks.

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HARMFUL EFFECTS OF THE RADIOACTIVITY FROM EXPLOSION OF PURE HYDROGEN BOMBS AND ORDINARY ATOMIC BOMBS

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An evaluation is made of the dangers to the population from long-lived radioactive products distributed over the whole globe after the explosion of an ordinary (fission) bomb and a pure hydrogen (fusion) bomb. The pure hydrogen bomb considered is a deuterium-tritium bomb.

Gonad and bone doses are calculated, with the resulting numbers of births with hereditary diseases and cases of leukemia (blood cancer). In the case of a hydrogen bomb the active elements are C^{14} and H^3, and for an ordinary bomb they are Sr^{90}, Cs^{137}, and C^{14}. The distribution of the radioisotopes in nature and in the organism is evaluated. The case of a ground burst of a hydrogen bomb is also considered. The total amount of energy from the radioactive decay of the explosion products of a deuterium-tritium bomb is greater by a factor of three than that for an ordinary bomb. The radiation dose to the tissues and the number of victims to radioactive fallout over all time are about the same for 10 megatons TNT equivalent of both types of bombs. These doses are (rounded off):

	Deuterium-tritium bomb	Ordinary bomb
Tissue dose	$50{,}000 \cdot 10^{-6}$ r	$40{,}000 \cdot 10^{-6}$ r
Bone dose	$50{,}000 \cdot 10^{-6}$ r	$88{,}000 \cdot 10^{-6}$ r
Number of mutants (per $2.5 \cdot 10^9$ people)	50,000	40,000
Number of leukemia cases (per $2.5 \cdot 10^9$ people)	15,000	26,000

Thus in terms of the radiation damage caused to the world population, a pure hydrogen (deuterium-tritium) bomb cannot be considered less dangerous than an ordinary bomb.

Any energetic atomic explostion causes effects not only in the burst region at the time of explosion, but over the whole earth for centuries and thousands of years later.

The extended effects of an atomic explosion are due to the radioactive elements formed in the burst and distributed relatively uniformly over the whole globe.

The purpose of the present work is to compare the relative dangers from the burst of an ordinary fission bomb and from that of a pure hydrogen deuterium-tritium bomb. This shall be based on a calculation of the radiation dose and the absolute number of diseases caused by the radioactive products of these bursts. The action of those radioisotopes is considered which are distributed over the whole globe; local effects in the neighborhood of the explosion are not treated.

1. Basic Biological and Physical Data

Quantitative criteria of danger. The effects here being considered are characterized by small radiation doses of long duration. The most important harmful effects (of those studied) of such radiation are genetic effects and the occurrence of malignant growths. A quantitative evaluation is possible for the number of mutant births (or the number of humans born with characteristics caused by mutant genes) and for one of the forms of malignant growths, namely leukemia (so-called cancer of the blood).

TABLE 1

Products of a 10 Megaton Burst

	Ordinary bomb burst	Pure hydrogen bomb burst
Number of fission events	$1.45 \cdot 10^{27}$	–
Number of events of the $H^2 + H^3$ reaction	–	$1.45 \cdot 10^{28}$
Number of neutrons emitted	$2.2 \cdot 10^{27}$	$1.45 \cdot 10^{28}$
Amount and decay energy of Sr^{90}	$6.7 \cdot 10^{25}$ atoms 10^4 g $1.43 \cdot 10^6$ Curies $6.7 \cdot 10^{25}$ Mev	–
Amount and decay energy of Cs^{137}	$8.7 \cdot 10^{25}$ atoms $1.57 \cdot 10^6$ Curies $7 \cdot 10^{25}$ Mev	–
Amount and decay energy of C^{14}	$2.2 \cdot 10^{27}$ atoms $5.2 \cdot 10^4$ g $2.34 \cdot 10^5$ Curies $1.1 \cdot 10^{26}$ Mev	$1.4 \cdot 10^{28}$ atoms $3.3 \cdot 10^5$ g $1.49 \cdot 10^6$ Curies $7.5 \cdot 10^{26}$ Mev
Amount and decay energy of H^3	–	$1.4 \cdot 10^{27}$ atoms $7 \cdot 10^3$ g $6.67 \cdot 10^7$ Curies $8.4 \cdot 10^{24}$ Mev
Total amount of radioactive products	$3.27 \cdot 10^6$ Curies	$6.8 \cdot 10^7$ Curies
Energy of radioactive products	$2.5 \cdot 10^{26}$ Mev	$7.5 \cdot 10^{26}$ Mev

* The values presented in this and other tables without naming sources have been obtained by the author on the basis of known data in the literature.

The number of mutant genes caused by radiation can be calculated on the basis of the genetic equilibrium established by the constant action of natural radiation on the human organism. The number of mutant genes eliminated from the population as a result of the death of mutants without reproduction is equal to the number of those produced as a result of radiation, and the number of mutations is proportional to the radiation dose.

Geneticists consider it established that 2% of all births are burdened by serious genetic diseases, which is to say that 2% of all births are associated with mutant genes [1]. By a conservative estimate 10% of this 2% is due to natural radiation at a rate of 0.18 r/yr, or 5.4 r in 30 years, so that natural radiation leads to the fraction $2 \cdot 10^{-2} \cdot 10 \cdot 10^{-2} = 2 \cdot 10^{-3}$ of mutants in all the progeny of a single person. The proportionality coefficient between dose and the fraction of mutant births is

$$\frac{2 \cdot 10^{-3}}{5.4} \approx 4 \cdot 10^{-4} \text{ mutants/birth} \cdot \text{r} .$$

In order to calculate the number of mutants which occur from one person, the above fraction must be multiplied by the number of births per person during his whole life, that is by $3 \cdot 10^{-2}$ births/yr · 30 yrs ≈ 1 birth/person.*

TABLE 2

Characteristics of the Radioactive Products of Explosions

	Cs^{137}	Sr^{90}	C^{14}	H^3
Lifetime (years)	47.6	40	8100	18
Gamma energy and mean β-energy per decay (Mev)	0.61* 0.187	None 1	None 0.053	None 0.006
Dose per atom per g of tissue (rad/yr)**	–	–	$1.05 \cdot 10^{-13}$	$5.32 \cdot 10^{-12}$
Dose from 10^{-12} Curies per g of tissue (rad/yr)	$1.12 \cdot 10^{-2}$	$1.86 \cdot 10^{-2}$	–	–
The same, per g of bone tissue ***	–	$9.3 \cdot 10^{-2}$	–	–
The number of μμC per g of tissue which gives rise to the maximum allowable dose of 1.8 r/yr (a_{mt})	160	100	–	–
The same, in the bone	160	20	–	–
The number of μμC/g of carrier in the organism which gives rise to the maximum allowable in dose of 1.8 r/yr**** (a_{mc}):				
in the bone	–	140	–	–
in other tissue	$6.85 \cdot 10^4$	$1.6 \cdot 10^6$	–	–

* The mean energy liberated per g of tissue per decay is 0.6 Mev when one accounts for incomplete absorption of γ-rays by the organism.

** In place of the roentgen, which is equal to 95 ergs/g of water, we use the rad, which is equal to 100 ergs/g of tissue. In the calculations we shall not differentiate between these.

*** Strontium does not settle in the bones homogeneously, and therefore local concentrations may be five times as great as the mean concentration.

**** Here we take carrier to mean a similar chemical element, such as potassium for Cs^{137} or calcium for Sr^{90}.

Thus the proportionality coefficient between the number of mutants and the dose per person is

$$N_r = 4 \cdot 10^{-4} \text{ mutants/birth} \cdot \text{r} \times 1 \text{ birth/person} =$$
$$= 4 \cdot 10^{-4} \text{ mutants/person} \cdot \text{r} .$$

* It is assumed that there are about 30 births per 1000 in the population per year.

The number of mutants is the product of N_r, the number of irradiated persons, and the radiation to the gonads.*

Leukemia is caused particularly by bone radiation. The probability of contracting the disease is proportional to the mean dose to all the bone and is $2 \cdot 10^{-6}$ cases/yr · person · r [2]. Therefore, a given radiation dose causes the following number of cases of the disease for each person:

$$N_l = 2 \cdot 10^{-6} \frac{\text{cases}}{\text{yr} \cdot \text{person} \cdot \text{r}} \cdot 60 \text{ yr}$$

$$= 1.2 \cdot 10^{-4} \frac{\text{cases}}{\text{person} \cdot \text{r}} .$$

The number of cases of the disease is equal to the product of N_l, the number of persons irradiated, and the radiation dose to the bone.

Other possible harmful effects are not accounted for, since quantitative criteria do not exist for them.

Basic physical data. We shall consider a pure hydrogen bomb, or a deuterium-tritium bomb which releases its energy by the reaction

$$_1H^2 + {}_1H^3 \rightarrow {}_2He^4 + n + 17{,}6 \text{ Mev}$$

The liberation of an energy of 180 Mev, equal to the energy liberated in one fission act, necessitates ten acts of the $_1H^2 + {}_1H^3$ reaction. In releasing 180 Mev, the fusion reaction gives rise to 10 neutrons, rather than the 1.5 neutrons arising from the fission reaction. These neutrons are captured by nitrogen in the air, forming C^{14} according to the $N^{14}(n, p)C^{14}$ reaction. In the explosion of a pure hydrogen bomb, we account for ten C^{14} atoms and one H^3 atom per 180 Mev energy released.

The radioactive fission fragments of importance are Sr^{90} ($4{,}6 \cdot 10^{-2}$ atoms per 180 Mev), Cs^{137} ($6 \cdot 10^{-2}$ atoms per 180 Mev), and C^{14} (1.5 atoms per 180 Mev). The number of C^{14} atoms produced in a fission burst is less by a factor of 7 than the number produced in a hydrogen bomb burst.

Table 1 gives the characteristics of the explosions of an ordinary and a pure hydrogen bomb of 10 megaton TNT equivalent.**

Table 2 gives the characteristics of the radioactive products of an explosion.

2. Method for Calculating C^{14} and H^3 Dose

Both C^{14} and H^3 are always found in nature. They are formed in the atmosphere by cosmic radiation. Their total quantity is in equilibrium, which means that it can be calculated by multiplying the production rate by the decay time. The C^{14} concentration is the same in various organic and inorganic compounds containing exchangeable carbon.

Atmospheric water has a definite concentration of H^3. All substances on the surface of the earth containing exchangeable carbon have a definite C^{14} concentration. The water and carbon in the human body should have the same C^{14} and H^3 concentrations as is found in foods.

After an explosion the total amount of C^{14} and H^3 in nature increases by a factor of $1 + \Delta A/A$ (where A is the equilibrium C^{14} or H^3 concentration before the burst, and ΔA is the amount of C^{14} or H^3 created in the burst). Then a new isotope concentration, greater by a factor of $1 + \Delta A/A$ than the previous, will be established in food and therefore in the human body.

Since the dose rate due to radioactive isotopes in the tissues is proportional to their concentration, the dose rate after a burst is greater by a factor $1 + \Delta A/A$ than that due to the natural C^{14} and H^3 concentration.

* According to other data which is equally probable, the mutant rate is not 2, but 4%, and the fraction of mutations due to natural radioactivity is 25%; then the number of genetic victims will be 4 times as great as that calculated in the present work.

** 10 megaton TNT equivalent is equal to 10^{13} kcal.

TABLE 3

C^{14} and H^3 Concentrations in Nature

	C^{14}	H^3
Rate of formation in the atmosphere (g/yr)	10^4* [5, 3]	100 [4]
The total amount on the earth (g), A**	$81 \cdot 10^6$	1800
The same, except for what is in the oceans (in the atmosphere, part of the biosphere, rivers) A'	$10 \cdot 10^6$ [3, 5]	24 [4]
Relative increase in the amount of the isotopes as a result of a pure hydrogen burst, $\Delta A/A$	$4.1 \cdot 10^{-3}$	3.9***
The same, accounting only for those isotopes outside the ocean, $\Delta A/A$	$33 \cdot 10^{-3}$	290
Natural atom concentration of the isotopes in plants (C^{14}) and river water (H^3)	$1.4 \cdot 10^{-12}$**** [3]	$5 \cdot 10^{-18}$ [2]

* This corresponds to 2.7 neutrons absorbed in the atmosphere per second over each square centimeter of the earth's surface.

** This is obtained by multiplying the production rate in the atmosphere by the decay time.

*** Careful measurements should detect the increase in the amount of H^3 in nature due to atomic explosions.

**** This corresponds to 16 decays of C^{14} per minute per g of C^{12} [3].

Let us denote the dose rate due to the natural C^{14} and H^3 concentration by p_0. Then the dose rate to tissues due to radioactive isotopes produced in an explosion is

$$p = p_0 \cdot \frac{\Delta A}{A}. \qquad (1)$$

Table 3 gives the concentration of C^{14} and H^3 in nature.

Assuming that the H^3 concentration in the water in an organism is the same as that in river water, and that the organism consists essentially of water (other hydrogen in the chemical composition of tissues is not accounted for) we can find the amount of H^3 per g of tissue water. Similarly, we assume that the C^{14} concentration in tissues is the same as that in the biosphere.

The composition of tissue and the values of p_0 are given in Table 4.

TABLE 4

Dose Rate Due to Natural* C^{14} and H^3 in the Tissues

Number of atoms per g of tissue [6]	Number of atoms of radioactive isotopes per g of tissue	Dose rate per atom per g of tissue, r/yr	Dose rate from natural isotope concentration p_0, r/yr
$H - 6.6 \cdot 10^{22}$	$3.3 \cdot 10^5$	$5.32 \cdot 10^{-12}$	$1.8 \cdot 10^{-6}$
$C - 1 \cdot 10^{22}$	$1.4 \cdot 10^{10}$	$1.05 \cdot 10^{-13}$	$1.5 \cdot 10^{-3}$

* The external radiation of C^{14} from CO_2 in the air gives a dose of 10^{-6} r/yr in the surface layers, which is not accounted for.

By using Eq. (1) with the values p_0 from Table 4 and $\frac{\Delta A}{A}$ from Table 3, we obtain the desired dose rates to the tissues from the radioactive products of a 10 megaton pure hydrogen burst. For an equilibrium distribution in the air, biosphere, and ocean we have

$$r\,C^{14} = 1.5 \cdot 10^{-3} \cdot 4{,}1 \cdot 10^{-3} = 6 \cdot 10^{-6}\ \text{r/yr};$$
$$r\,H^{3} = 1.8 \cdot 10^{-6} \cdot 3{,}9 = 7 \cdot 10^{-6}\ \text{r/yr}. \qquad (2)$$

The total dose rate of internal radiation is $13 \cdot 10^{-6}$ r/yr. Accounting for delayed interaction with the ocean, we have

$$r\,C^{14} = 1.5 \cdot 10^{-3} \cdot 33 \cdot 10^{-3} = 50 \cdot 10^{-6}\ \text{r/yr};$$
$$r\,H^{3} = 1.8 \cdot 10^{-6} \cdot 290 = 523 \cdot 10^{-6}\ \text{r/yr}. \qquad (2')$$

This total dose rate of internal radiation is $573 \cdot 10^{-6}$ r/yr* which is forty times greater than that with rapid absorption of the elements by the ocean.

It should be noted that the radiation from C^{14} will keep acting for thousands of years after the explosion, whereas that from H^3, Cs^{137}, and Sr^{90} will decay in a century. If one speaks of the effect on the generations in whose lifetime the explosion took place, the dose rate is important for the first half century, and then the question of the kinetics of radioisotope absorption by the ocean becomes significant. To compare effects which are proportional to the radiation dose (the total number of mutations and leukemia cases), the total dose for all time of the radioactive decay is important, and in the case of C^{14} it is measured in terms of thousands of years; therefore we shall assume that the radioisotopes are uniformly distributed throughout nature.

If we consider the fallout of H^3 onto the surface of the earth to occur with the same time constant as that of Sr^{90} (with a period of 10 years), then the H^3 dose for all time is

$$D_{H^3} = 7 \cdot 10^{-6}\ \text{r} \cdot 11{,}6\ \text{yr} = 81 \cdot 10^{-6}\ \text{r}^{**},$$

and that from C^{14} is

$$D_{C^{14}} = 6 \cdot 10^{-6}\ \text{r} \cdot 8{,}1 \cdot 10^{3}\ \text{yr} = 49\,000 \cdot 10^{-6}\ \text{r}^{***}).$$

In the case of a fission bomb, the C^{14} dose is smaller by a factor of seven, or $7000 \cdot 10^{-6}$ r.

3. The Method of Calculating the Sr^{90} and Cs^{137} Dose

We shall use the following notation:

Q(t) is the amount of radioisotope which has settled onto the earth assuming complete precipitation of fragments from a Q megaton burst.

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* The accuracy of this estimate is unknown in view of the absence of data on the kinetics by which the C^{14} and H^3 distributions are established. In calculating the dose rate it is important whether or not equilibrium is established with the ocean when the isotopes are spread through nature. The ocean absorbs a large part of the C^{14} and H^3 produced, and removes them from the biosphere. Therefore, if the distribution in the ocean is established at a much slower rate than that in the air and on the terrestrial part of the biosphere, the whole concentration of the products will be distributed only in the atmosphere, rivers, and terrestrial part of the biosphere. This will cause $\Delta A/A$, and therefore the dose rates, to be correspondingly greater. In what follows we use only that estimate which assumes an equilibrium distribution of radioisotopes through the air, biosphere, and ocean.

** The 40-year dose is smaller by a factor of 1.13.

*** The dose during the first 40 years is $180 \cdot 10^{-6}$ r if one assumes that the fallout from the stratosphere is similar to that of Sr^{90} (with a time constant of about 10 years).

Q_0 is the amount of radioisotope produced in the burst.

T_d is the decay time constant of the radioisotope.*

T_p is the time constant of precipitation.

T_{ep} is the effective time constant of precipitation from the stratosphere ($T_{ep} = \frac{T_d \cdot T_p}{T_d + T_p}$, T_p = 10 years).**

T_b is the time constant with which the radioisotope is eliminated from the organism.

T_{eb} is the effective time constant of elimination from the organism $\left(T_{eb} = \frac{T_d \cdot T_b}{T_d + T_b}\right)$.

ν is the amount of radioisotope entering daily into a critical organ at a precipitation rate corresponding to 1 megaton (in $\mu\mu$C/yr·megaton).

q(t) is the amount of radioisotope in an organ (in $\mu\mu$C).

M is the mass of the organ, tissue, or carrier element (in g).

a_{mt} is the maximum allowable radioisotope concentration at which the dose rate is 1.8 r/yr (in $\mu\mu$C/g of tissue) (see Table 2).

a_{mc} is the same in $\mu\mu$C per g of carrier.

a_m is the same without the choice of units being given (the choice of units depends on those chosen for M).

a(t) is the radioisotope concentration in the tissue (in $\mu\mu$C per g of tissue), given by

$$a(t) = \frac{q(t)}{M}.$$

The dose rate in the tissues is

$$r(t) = \frac{a(t)}{a_m} \cdot 1{,}8\,\text{r/yr} = \frac{q(t)}{a_m M} \cdot 1{,}8 \cdot \text{r/yr} \tag{3}$$

The dose in the tissues is

$$D(t) = \int p\,dt = \frac{1.8}{a_m M} \cdot \int q\,dt. \tag{4}$$

We can find q(t) from the equations

$$\frac{dq}{dt} = \nu Q - \frac{q}{T_{eb}}; \quad Q = Q_0 (e^{-t/T_d} - e^{-t/T_{ep}}), \tag{5}$$

$$q = \nu \cdot Q_0 \cdot T_{eb} \cdot f(t), \tag{6}***$$

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* In all calculations the time constants T give the time in which the original value decreases by a factor of e.

** The process of radioisotope precipitation from the stratosphere has not been very well studied. At the present level of knowledge one may assume, with Libby [10], that the precipitation takes place exponentially with the time constant of 10 years.

*** For continuous testing we have

$$q(t) = \nu T_{eb} Q_\infty F(t). \tag{6a}$$

where

$$f(t)=\left[\frac{T_d\cdot e^{-t/T_d}}{T_d-T_{eb}}-\frac{T_{ep}e^{-t/T_{ep}}}{T_{ep}-T_{eb}}-\right.$$
$$\left.-\left(\frac{T_d}{T_d-T_{eb}}-\frac{T_{ep}}{T_{ep}-T_{eb}}\right)e^{-t/T_{eb}}\right] \tag{6b}$$

After performing the integration we obtain

$$\left.\begin{aligned}&\text{for}\quad Cs^{137}\text{:}\quad D_{Cs}=\frac{1{,}8}{a_m M}\nu\cdot Q_0 T_{eb}\ 39.3^{*}\ ;\\ &\text{for}\quad Sr^{90}\text{:}\quad D_{Sr}=\frac{1{,}8}{a_m M}\cdot\nu\cdot Q_0\cdot T_{eb}\cdot 32.2.\end{aligned}\right\} \tag{7}$$

The quantity ν can be determined in one of the following two ways.

1. One can use experimental data on the radioisotope concentration in the human organism resulting from high-energy atomic bursts that started in 1952.

If the radioisotope concentration at time t_0 (counting from 1952) is $\frac{q(t)}{M}$, then using Eq. (6a) one can find ν or $\nu\cdot T_{eb}$ by

$$\nu\cdot T_{eb}=\frac{q(t_0)}{Q_\infty F(t)}=\frac{q(t_0)}{350\,F(t_0)}\cdot \tag{8}$$

Since the experimental data refers not to discontinuous pulses of bursts, but to continuous testing, Q_0 in Eq. (6) can be replaced by Q_∞, which corresponds to the amount of fallout on the earth after constant-intensity testing for an infinitely long time, as in Eq. (6a). It can be shown that for Sr^{90} we obtain Q_∞ = 350 megatons for a testing intensity of 11 megatons/yr.

2. One can use the known radioisotope concentration in the earth and a "discrimination factor" characterizing the decrease of this concentration on going from the earth to the human organism. This discrimination factor is calculated from the fact that cesium enters the organism together with potassium, and that strontium enters with calcium.

Since the chemical properties of cesium are not exactly those of potassium, and those of strontium are not exactly those of calcium, the radioisotope concentration in the carriers (potassium and calcium) is not the same in the soil as it is in the human organism. In other words one may write

$$\left(\frac{Sr}{Ca}\right)_{tiss.}=\left(\frac{Sr}{Ca}\right)_{soil}\cdot K,$$

where K is the total discrimination factor ($K = k_1k_2k_3k_4$, where k_1 corresponds to going from the soil to plants, k_2 from the plants to food (milk, meat, etc.), k_3 from the food to blood, and k_4 from the blood to the tissues).

It is obvious that the more calcium or potassium there is in the soil, the less radioisotope there will be in the organism. The value of K may be very small (for strontium it is about 0.02), and

$$\nu=AKm, \tag{9}$$

where A is the amount of radioactive substance (in $\mu\mu C/g$ of carrier) in the cultivated layer of soil as a result of precipitation onto the whole earth of an amount of isotope corresponding to a 1 megaton burst (assuming that

* The dose in 40 years will be smaller by a factor of 1.5.

the cultivated soil layer is 10-15 cm thick), and m is the rate at which the carrier element (potassium or calcium) is ingested by the human body (in g/yr).

Calculated of the Sr^{90} dose to the gonads.* The experimental data on the Sr^{90} concentration in the human skeleton at the end of 1955 has been investigated by Kulp and co-workers [7].

At the end of 1955 it was found [7] that the Sr^{90} concentration in the soil was 3.2 $\mu C/km^2$ which is about what one would get from the complete precipitation of the Sr^{90} produced in the burst of an ordinary 10 megaton bomb (2.9 $\mu C/km^2$). The mean Sr^{90} concentration in bone corresponding to this was found to be 0.3 $\mu\mu C/g$ of Ca. This figure refers to children four years old and under, for whom the rate of calcium ingestion is greatest, and the majority of whose lives took place after the first large American bursts (1952-1953). This figure is greater by a factor of 3 than the average concentration for all ages, namely 0.1 $\mu\mu C/g$ of Ca.

In the given case t_0 = 4 years, so that F(t) = 0.0025. Inserting this value of $F(t_0)$ into (8), we obtain

$$\nu T_{eb} = \frac{q(t_0)}{350\,F(t_0)} = \frac{0.3\ \text{gCa}\ M(t_0)}{350 \cdot 0.0025}\ \frac{\mu\mu C}{\text{megaton/organism}}$$

where $M(t_0)$ is the mass of the organ (in the present case the mass of calcium in the skeleton) at four years. Inserting the value obtained for νT_{eb} into (7) and setting $a_{mc} = 1.16 \cdot 10^6$ $\mu\mu C/g$ Ca (see Table 2), we obtain the gonad dose**

$$D = \frac{1.8 \cdot M(t_0) \cdot 0.3 \cdot 32.2}{1.16 \cdot 10^6 \cdot M \cdot 350 \cdot 0.0025} \cdot 3 = 128 \cdot 10^{-6}\ \text{r}$$

(where M(4 yrs)/M = 1/4 is the ratio of the weight of calcium in the organism of a child to that in the organism of an adult).

Calculation of the bone dose of Sr^{90}. Inserting the value of νT_{eb} obtained in section A, the value a_{mc} = = 140 $\mu\mu C/g$ Ca (see Table 2), and the value $M(t_0)/M = 1/4$ into (7), we obtain the bone dose

$$D_B = 0.36\ \text{r}\ .$$

The mean dose rate is 0.36 r/32.2 yrs = 11.2 mr/yr.

The dose calculated refers to the most strongly irradiated areas in which strontium accumulates. The mean dose over all bone tissue is lower by a factor of 5 (international standard), or 0.072 r. In estimating the frequency of leukemia, one should use the mean dose over the whole skeleton (see Section 1).

Calculation of the Cs^{137} radiation dose to the tissues. We may determine ν by either one of the two methods described above; and shall give both calculations here.

1. At the end of 1956 the cesium concentration was measured on living persons and established at 30 $\mu\mu C/g$ potassium [8]. Since in 1956 the amount of precipitates on the earth's surface corresponded to 10 megatons, and the cesium concentration was in equilibrium with this value (the elimination time constant of cesium and potassium from the organism are small, of the order of a month), we have

$$\nu T_{eb} \doteq \frac{q^{***}}{Q} = \frac{30\ \mu\mu C/g\ \text{potassium} \cdot 140\ g}{10\ \text{megatons}} = 420\ \mu\mu C/\text{megaton}$$

* We shall calculate ν by method 1.

** The multiplication by a factor of 3 is performed because $a(t_0)$ was determined for bones, which have a discrimination factor of 3 with respect to the blood. In the blood and therefore in the gonads the concentration is three times as great as in the bone.

*** $T_{eb} \ll t, T_d T_{ep}$. In this case $\nu T_{eb} = \frac{q}{Q}$.

(there are 140 g of potassium in the organism) [9].

Inserting the value obtained into (7) and taking a_{mc} from Table 2 (namely $6.85 \cdot 10^4$ $\mu\mu C/g$ potassium), we obtain

$$D = \frac{1.8 \cdot 420 \cdot 10 \cdot 39.3}{6.85 \cdot 10^4 \cdot 140} = 31\,000 \cdot 10^{-6} .$$

The mean dose rate is equal to $750 \cdot 10^{-6}$ r.

2. The assimilation of Cs^{137}, Sr^{90}, potassium, and calcium by plants was measured by Guliakin and Iudintseva [10] and their figures can be used together with the known discrimination factor for Sr^{90} on going from soil to plants (0.7) [7] to attain an estimate of the discrimination factor on going from soil to plants for Cs^{137}. Such calculation gives 1/700, and

$$\nu = AKm = \frac{1.57 \cdot 10^{17} \frac{\mu\mu C}{\text{megaton}}}{10^{-4} \frac{g\,K}{g\,\text{soil}} \cdot 5 \cdot 10^{18}\ см^2 \cdot 10\ см \cdot 1.6 \frac{g}{см^3}} \times$$

$$\times \frac{1}{700} 1000\ gK/yr = 28.6 \frac{\mu\mu C}{\text{megaton} \cdot \text{yr} \cdot \text{organism}} ;$$

$$\nu T'_{eb} = 28.6 \cdot 6.85 \cdot 10^{-2} = 2 \frac{\mu\mu C}{\text{megaton} \cdot \text{organism}}$$

(T'_{eb} = 25 days $= 6.85 \cdot 10^{-2}$ yrs. [8]).

Then according to (7) we obtain

$$D = \frac{1.8 \cdot 2 \cdot 10 \cdot 39.3}{6.85 \cdot 10^4 \cdot 140} = 148 \cdot 10^{-6}\ \text{r}.$$

The first and second evaluations differ by the large factor of 210. This may possibly be explained by the fact that cesium precipitates onto leaves themselves and is assimilated by plants without passing through the soil. This form of assimilation is highly efficient.

We consider the first evaluation to be correct, since it is based on direct measurements; it will thus be used in the calculations.

Calculation of the Cs^{137} bone dose. It is assumed that cesium is distributed homogeneously through the bones together with potassium. Then the bones contain 1/30 of all the cesium, and νT_{eb} = 420/30 = 14 $\mu\mu C$/megaton. Inserting this into (7), taking a_{mt} to be 160 $\mu\mu C/g$ of tissue, and setting $M = 10^4$ g, we obtain $D = 6200 \cdot 10^{-6}$ r.

Calculation of the external Cs^{137} γ-radiation dose. The external radiation dose can be calculated from the formula for the dose rate from a semi-infinite volume (the soil) with an equilibrium concentration of activity g Mev/$cm^3 \cdot yr$,* namely

$$p = \alpha \cdot 1.48 \cdot 10^{-5} \mu_{0E} g \frac{\lambda_{eff}}{2},$$

where α and λ_{eff} are the coefficients in the equations for passage of Cs^{137} γ-radiation through the soil, and $1.48 \cdot 10^{-5}$ is the factor for converting Mev/cm^3 into r. Then the intensity of the radiation that has passed through the soil is $\alpha \cdot e^{-x/\lambda_{eff}}$ (where x is the soil thickness, α = 1.3, and λ_{eff} = 12 cm), and μ_{0E} is the energy absorption coefficient in air, equal to $3.8 \cdot 10^{-5}$ cm^{-1}. Then

*$g \approx Q$; therefore according to (5) $g = g_0 (e^{-t/T_d} - e^{-t/T_{ep}})$.

$$g_0 \frac{\lambda_{eff}}{2} = \frac{Q_0 \text{Cur.}}{5 \cdot 10^{18}\ см^2 \cdot 15\ см \cdot 2} \frac{3.7 \cdot 10^{10} \text{sec}^{-1}\ 0.6 \text{Mev}}{} \times$$
$$\times 12\ см \cdot 3.15 - 10^7 \frac{\text{sec}}{\text{yr}} = 8.8 \cdot 10^4 \frac{\text{Mev}}{см^2 \cdot \text{yr}},$$
$$r = 64.3 \cdot 10^{-6} (e^{t/T_d} - e^{t/T_{ep}})\ r/\text{yr}$$

where $5 \cdot 10^{18}$ cm^2 is the area of the earth, 15 cm is the thickness of the earth's layer containing radiation sources, and $Q_0 = 1.57 \cdot 10^6$ Curies corresponds to a burst energy of 10 megatons (see Table 1). The external Cs^{137} radiation dose over all time is

$$\int_0^\infty r dt = 2540 \cdot 10^{-6}\ r.$$

4. Comparison of the Doses During the Isotope Lifetimes and Estimate of Number of Disease Cases

Since the number of mutations is proportional to the total gonad dose, comparison of the genetic consequences of ordinary and deuterium-tritium bombs can be performed on the basis of the total gonad dose during the isotope lifetime. This is done in Table 5.

TABLE 5

Gonad Radiation Dose for Ordinary and Pure Hydrogen Bomb Bursts

Radiation source	Dose, r	
	ordinary bomb bursts	pure hydrogen bomb bursts
Sr^{90}	$128 \cdot 10^{-6}$	–
Cs^{137}	$31{,}000 \cdot 10^{-6}$	–
C^{14}	$7000 \cdot 10^{-6}$	$49{,}000 \cdot 10^{-6}$
H^3	–	$81 \cdot 10^{-6}$
Cs^{137} (external)	$2540 \cdot 10^{-6}$	–
Total dose over the lifetime of the isotope	$41{,}000 \cdot 10^{-6}$	$49{,}000 \cdot 10^{-6}$

TABLE 5a

Radiation source	30-year dose, r	
	ordinary bomb burst	pure hydrogen bomb burst
Internal	$15{,}000 \cdot 10^{-6}$	$190 \cdot 10^{-6}$ to
External	$1900 \cdot 10^{-6}$	$5300 \cdot 10^{-6}$ *

* The dose of $5300 \cdot 10^{-6}$ r is obtained on the assumption that in 30 years the ocean is not able to absorb a significant amount of C^{14}.

Thus, the total dose over all time from a pure hydrogen bomb is close to the total dose from an ordinary bomb. A similar picture is obtained on considering the dose to the tissues over the first 30 years after the explosion (see Table 5a).

As time goes on, the dose rate will decrease due to the decay of Cs^{137}, Sr^{90}, and H^3. A century and more after an explosion the only significant effects will be those of C^{14}, and these will go on for many thousands of years.

Let us perform an evaluation of the genetic damage due to C^{14} from a 10 megaton pure hydrogen bomb.

The total number of mutant births during the decay time of an isotope is given by the total dose,* and this can be evaluated with the aid of a coefficient of genetic harm (Section 1).

* Proportionality between the dose and the total number of victims over infinite time is valid only if the time in which the equilibrium radioisotope concentration is established in the organism is much less than the lifetime of the organism, as is true for C^{14}, Cs^{137} and H^3. For Sr^{90} this condition is not as well fulfilled, but calculation shows that the error is not great. An accurate calculation of the number of victims would require accounting for the age distribution of the population at the time of the burst. A calculation based on a numerically constant population having two age groups (0 and 30 years) at the time of burst gives a value lower than that of Eq. (7) by a factor of 1.3 for the number of Sr^{90} victims.

TABLE 6

Mean Bone Radiation Dose

Radiation source	Bone radiation dose, r	
	ordinary bomb burst	pure hydrogen bomb burst
Sr^{90}	$72\,000 \cdot 10^{-6}$	—
Cs^{137}	$6200 \cdot 10^{-6}$	—
C^{14}*	$7000 \cdot 10^{-6}$	$49\,000 \cdot 10^{-6}$
H^3	—	Not accounted for
Cs^{137} (external)	$2540 \cdot 10^{-6}$	—
Total bone dose over the radioisotope lifetimes	$88\,000 \cdot 10^{-6}$	$49\,000 \cdot 10^{-6}$

* It is assumed that the carbon concentration in the organic part of the skeleton is the same as in the tissues.

In a sample of $2.5 \cdot 10^9$ persons, the total number of mutant births is the following:

from C^{14}: $2.5 \cdot 10^9$ persons$\times 4 \cdot 10^{-4}$ mutants/persons $\cdot$ r$\times 49{,}000 \cdot 10^{-6}$ r = 49,000 persons;

from H^3: $2.5 \cdot 10^9$ persons$\times 4 \cdot 10^{-4}$ mutants/persons $\cdot$ r$\times 81 \cdot 10^{-6}$ r = 81 persons.

The total number of mutant births from a 10 megaton pure hydrogen bomb is 49,000.

Comparison with the data of Table 5 shows that an ordinary fission bomb burst leads to roughly the same number of victims as a fusion bomb burst.

For nongenetic effects, a quantitative evaluation can be given only for the number of leukemia cases. The number of leukemia cases is proportional to the radiation dose to the bone and is $1.2 \cdot 10^{-4}$ cases/person $\cdot$ r.

In Table 6 we present the mean bone radiation dose over the lifetime of the radioisotopes. In the explosion of an ordinary bomb a large part of the leukemia cases arises during the first 50 years, which is the effective time constant of the Sr^{90} and Cs^{137} action. For a pure hydrogen bomb burst, about the same number of cases occur over thousands of years. We assume that proportionality between the number of the cases and the dose can be extended to irradiation over thousands of years.

The total number of leukemia cases from a 10 megaton pure hydrogen bomb burst in a population of $2.5 \cdot 10^9$ persons is

$$2.5 \cdot 10^9 \text{ persons} \cdot 1.2 \cdot 10^{-4} \frac{\text{cases}}{\text{persons}} \cdot 49{,}000 \cdot 10^{-6} = 15{,}000 \text{ persons.}$$

According to Table 6 an ordinary bomb burst causes 26,000 cases.

5. Effects of a Ground Burst of a Pure Hydrogen Bomb

In the case of a ground burst of a pure hydrogen bomb there will occur additional radioactive products, namely the isotopes produced by neutron capture in the soil. Much of the radioactivity so produced is of short duration and can be ignored. Activities with lifetimes greater than 5 years come from the isotopes Co^{60}, Cs^{137}, Sm^{151}, and Eu^{154}. The last two of these concentrate in the bone in a way similar to strontium. Insufficiently well established data on the distribution of these elements in nature and in the human body, as well as insufficient data on their metabolism, allows one to make only a preliminary estimate for cobalt alone.

We assume that the soil is composed of 10^{-5} cobalt, and that animal tissue is composed of 10^{-6} cobalt (BSE, vol. 21, 1957, p. 489). In a single radioactive event 1 Mev of energy is absorbed by the tissue; the lifetime is 8 years.* The fraction of radioactive cobalt in the organism will be equal to the fraction of the radioactive cobalt in the soil. The latter is equal to the ratio between the number of radioactive cobalt atoms produced and the number of cobalt atoms in the upper soil layer of the earth. The capture cross section of cobalt per g of earth is 10^{-5} g Co/g soil $\cdot 10^{22}$ atoms/g $\cdot 60 \cdot 10^{-24}$ cm^2/atoms = $6 \cdot 10^{-6}$ cm/g. Since the capture cross section of earth is $5 \cdot 10^{-3}$ cm^2/g, it follows that the cobalt will capture $(6 \cdot 10^{-6})/(5 \cdot 10^{-3}) = 10^{-3}$ of all the

* We are again speaking of the time it takes the original quantity to decrease by a factor of e.

neutrons, which will result in the formation of $0.5^{*} \cdot 10^{28} \cdot 10^{-3} = 5 \cdot 10^{24}$ atoms of radioactive cobalt. In a layer of thickness $\sim$ 20 g/cm^2 of the earth's surface there are $5 \cdot 10^{18}$ cm$^2 \cdot 20$ g/cm$^2 \cdot 10^{-5} = 10^{15}$ g of cobalt, or $(10^{15} \cdot 6 \cdot 10^{23})/60 = 10^{37}$ atoms of cobalt. Thus, the radioactive cobalt would be $5 \cdot 10^{24}/10^{37} = 5 \cdot 10^{-13}$ of all the cobalt. Then for equilibrium there would be $10^{-6} \cdot 5 \cdot 10^{-13} = 5 \cdot 10^{-19}$ g of radioactive cobalt per g of tissue in the animal organism, or

$$5 \cdot \frac{10^{-19}}{60} \cdot 6 \cdot 10^{23} = 5 \cdot 10^{3} \frac{\text{atoms}}{\text{g}} \text{Co}^{60}.$$

The dose rate from cobalt is $5 \cdot 10^{3}$ atoms/g $\cdot$ 1 Mev/atom $\cdot 1.6 \cdot 10^{-6}$ erg/Mev $\cdot 10^{-2}$ r/erg $= 11 \cdot 10^{-6}$ r/yr.** The dose for the whole decay time is $90 \cdot 10^{-6}$ r. Thus the contribution due to cobalt is not great.

The behavior of Sm^{151} and Eu^{154} is of interest, since like Sr^{90} they settle in the bone and are not eliminated (although the assimilation coefficient for a single intake of food is 1000 times less for these than for Sr^{90}) [11].

For fission or pure hydrogen bombs different from those considered in the present article, the dose and the effects change in proportion to the number of fission events and number of neutrons produced in the bursts.

SUMMARY

From the point of view of the harmful after-effects (number of mutant births and leukemia cases) calculated from the magnitude of the radiation dose, a pure hydrogen (deuterium-tritium) bomb is as dangerous as an ordinary fission bomb, but the after-effects will be extended over a longer time.

The total number of genetic victims to a 10 megaton pure hydrogen bomb in a population of $2.5 \cdot 10^{9}$ persons is estimated as 49,000, whereas that from an ordinary burst is estimated at 41,000. The total number of leukemia cases from a 10 megaton pure hydrogen bomb is estimated at 15,000, whereas that from an ordinary burst is estimated at 26,000.

The author considers it his pleasant duty to thank A. P. Vinogradov, N. P. Dubinin, V. M. Klechkovskii, A. V. Lebedinskii, and A. D. Sakharov for valuable discussion of the questions considered, and for advice.

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* The earth captures half of all the neutrons.

** This number is actually too large, since 1) neutron capture occurs in a ground layer about 15 cm thick, all of which is not carried into the stratosphere, and 2) precipitation of ground particles takes place at a more rapid rate. Therefore, the amount of Co^{60} distributed over the world will be less. In a restricted locality the Co^{60} dose may be significant.

LETTERS TO THE EDITOR

SPECTRA OF SECONDARY NEUTRONS PRODUCED BY NEUTRONS PASSING THROUGH VARIOUS SUBSTANCES

Iu. S. Zamiatnin, E. K. Gutnikova, N. I. Ivanova, and I. N. Safina

Between 1950 and 1956 the authors have measured the spectra of secondary neutrons produced by passing 14-Mev neutrons through the following substances: Li^6, Li^7, beryllium, boron, carbon, magnesium, aluminum, iron, copper, molybdenum, cadmium, antimony, tungsten, mercury, lead, and bismuth.

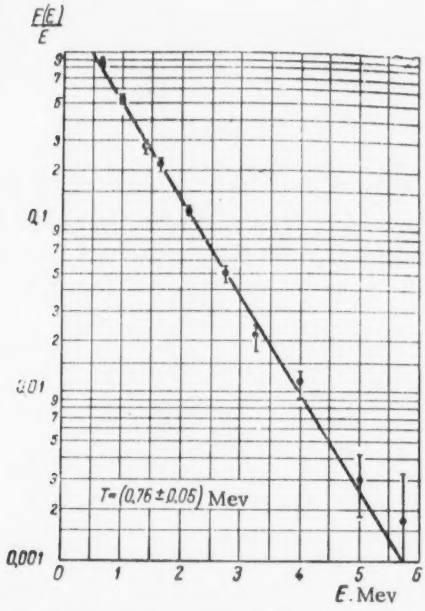

Fig. 1. Spectrum of secondary neutrons produced when 14-Mev neutrons pass though a thickness of copper of about 0.3 λ.

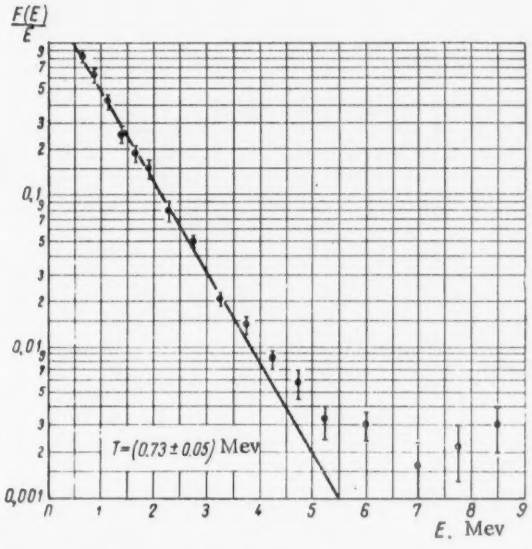

Fig 2. Spectrum of secondary neutrons produced when 14-Mev neutrons pass though a thickness of lead of about 0.3 λ.

The 14-Mev neutrons were obtained from the T(d, n)He^4 reaction. The neutron detectors were Ilford S-2 and NIKFI type K photographic emulsions 100μ thick. The neutron source was surrounded by a spherical shell of thickness about λ/3 made of the element being investigated. The photographic plates were located at a distance $l \approx 4R$ (where R is the external radius of the sphere).

For each substance, we measure between 1500 and 2000 recoil proton tracks in the forward direction ($\theta_{max} \approx \pm 15°$). In order also to account for the background due to the primary neutrons, we irradiated photographic plates under the same conditions but without the spherical shell surrounding the source. In subtracting the background, it was assumed that the number of background tracks is proportional to the number of primary neutrons incident on the photographic plate. The secondary neutron spectra were found from the experimentally obtained

Values of T Obtained From Experiments on the Inelastic Interaction of 14-Mev Neutrons with Various Nuclei

Element	Atomic weight	T, Mev (data from various authors)					Our results
		Gugelot* [1]	Stelson, Goodman[2]	Whitemore, Dennis [3]	Graves, Rosen [4]	O'Neill [5]	
Li	6						0.78±0.08
Li	7						0.8±0.08
Be	9	0.9±0.1					0.7±0.07
B	11						0.75±0.1
C	12				1.04±0.11	0.93	0.82±0.08
Mg	24						0.98±0.08
Al	27	1.3±0.1	1.1		1.01±0.1	1.06	1,13±0.08
Fe	56	0.95±0.1	0.6		0.76±0.08		0.7±0.07
Cu	64				0.77±0.08	0.82	0.76±0.06
Zn	65				0.73±0.07		
Mo	96						0.65±0.06
Rh	103	0.85±0.1					
Ag	108				0.63±0.06		
Cd	112				0.66±0.07		0.62±0.05
Sn	119				0.56±0.06	0.62	
Sb	122						0.6±0.06
W	184						0.62±0.08
Au	197	0.8±0.1			0.66±0.07		
Hg	201						0.6±0.05
Tl	204	0.78±0.1					
Pb	207		0.7	0.8	0.76±0.08	0.75	0.73±0.05
Bi	209			0.9	0.95±0.1		0.9±0.08

* The values of T are obtained from neutrons from the (p, n) reaction with 16-Mev protons.

range distributions of the recoil protons registered, accounting for the finite thickness of the emulsion and the energy dependence of the cross section for (n, p) scattering.

According to the collective theory, the spectra investigated give the energy distribution of the neutrons evaporated from the compound nucleus, that is,

$$F(E)=C\cdot E\cdot e^{-\frac{E}{T}}, \qquad (1)$$

where C is a normalizing constant, and T is a parameter characterizing the temperature of the residual nucleus.

Figures 1 and 2 give examples of the spectra of inelastically scattered neutrons from copper and lead. The values of T obtained from the $\frac{F(E)}{E}$ curves are given in the table together with the results of other authors.

In the spectra studied, in addition to inelastically scattered neutrons there were also neutrons from the (n, 2n) reaction, and these have more complex spectra due to the different temperatures at which the first and second neutron are evaporated. Because of the insufficiently accurate measurements, however, we did not succeed in resolving these neutrons.

It is seen from the table that for medium and heavy ($25 \leqslant A \leqslant 200$) nuclei T decreases as A increases,* until it is about one-half of its original value. This is in qualitative agreement with the statistical theory. For the lightest nuclei ($A \approx 5$-10), to which statistical considerations cannot be applied, the T values obtained are somewhat smaller than those for $A \approx 25$. In addition, the magic nuclei lead and bismuth, which have closed orbits and large separations between the energy levels, do not follow this general rule.

These measurements show that at energies above 4-5 Mev there is a deviation from the distribution given by (1). This can be explained by the evaporation of neutrons from local hot points in the nucleus. The poor

*For the fissile nuclei of thorium, uranium, etc., T is about 0.5 Mev [6].

experimental statistics in this energy region, however, will not yet permit quantitative estimates of the probabilities for such a process for most of the elements measured. We performed more detailed investigations of the secondary neutron spectra for this energy range only for beryllium, mercury, and lead.

In order to obtain more information on the mechanism of production of neutrons with energies greater than 3 Mev, we are at present making further measurements of their energy and angular distributions.

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MEASUREMENTS OF NEUTRON SPECTRA FOR ENERGIES BELOW 0.5 Mev BY A TIME-OF-FLIGHT METHOD

Iu. A. Vasil'ev, Iu. S. Zamiatnin, P. V. Toropov, and E. F. Fomushkin

Until recently, the study of neutron spectra for energies less than 0.5 Mev presented great difficulties due to the lack of reliable measurements. Measurements by means of a hydrogen-containing proportional counter and a cloud chamber [1] are extremely difficult and do not always give sufficient accuracy. A more hopeful method for measuring neutron spectra in this energy region is a time-of-flight measurement.

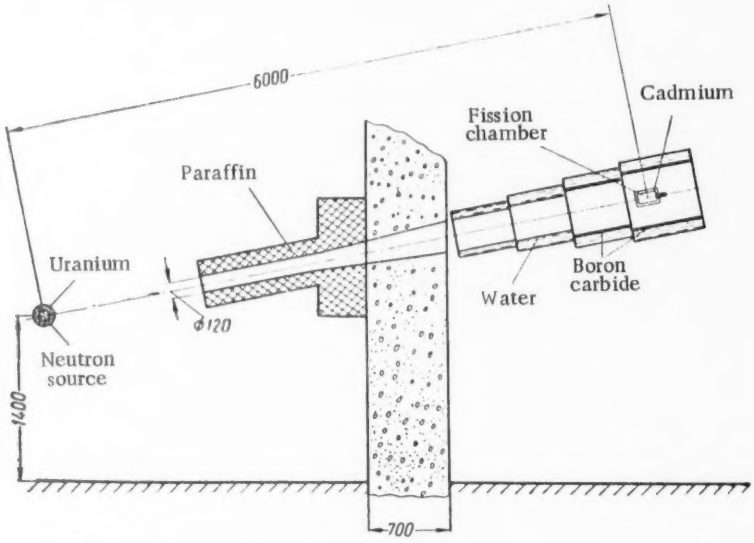

Fig. 1. Experimental geometry.

In our experiment this method together with a pulsed neutron source was used to measure the spectra of neutrons produced by 14-Mev neutrons passing through thicknesses of uranium.

The primary 14-Mev neutrons were obtained from the T(d, n)He^4 reaction in a low-energy accelerating tube. Pulse operation of the tube was obtained by modulating the deuteron beam by voltage pulses applied to a deflecting plate. The measurements were performed with neutron pulses lasting 10^{-7} sec at a repetition frequency of 120 kc. The spectra were studied by surrounding the target of the accelerator by a shell of the substance being investigated.

The neutron detector was a multilayer fission chamber containing about 0.5 g of U^{235} and giving pulses with a rise time of 0.1 μsec.

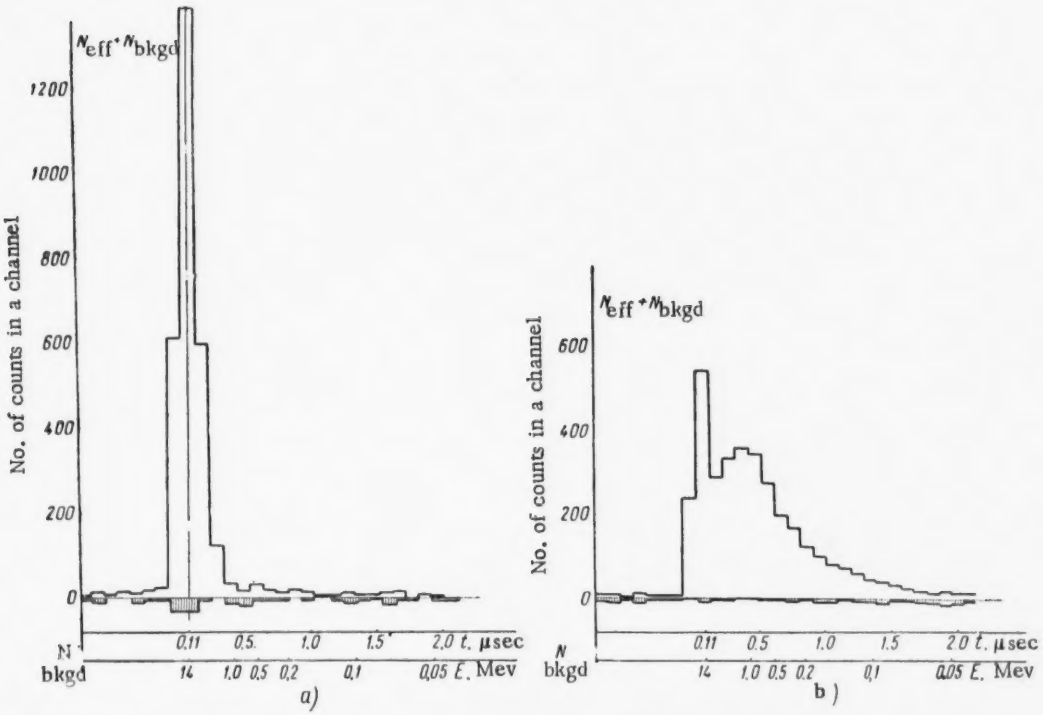

Fig. 2. Time distributions of detector pulses for recording a) 14-Mev neutrons, and b) the spectrum produced by 14-Mev neutrons passing through an 8 cm layer of U^{238}. The number of counts in the channels are normalized to the same primary neutron flux.

The distance of flight from the neutron source to the detector was 6 m. To provide shielding from scattered neutrons, the detector was located behind a concrete wall, the neutron beam was collimated, and a system of shielding blocks was used. The experimental geometry is given in Fig. 1.

The pulse used to indicate the time at which the neutron pulse was formed was obtained from the deuteron current pulse on the target of accelerating tube. The time distribution of the detector pulses was measured by a thirty-channel time analyzer of the chronotron type with a channel width of 0.1 μsec.

Figure 2 shows the time distributions of the detector pulses obtained in recording 14-Mev neutrons and neutrons formed by the passage of the primary neutrons through an 8 cm thick layer of U^{238}. The time and energy scales were calibrated from the position of the 14-Mev neutron line. The half-width of the line, 0.2 μsec, determined the resolving power of the spectrometer. The energy resolution was ±15% at a neutron energy of 100 kev.

The neutron background of the detector was caused mostly by neutrons passing through the shielding and the inherent background of the fission chamber, and was measured with the collimator channel closed. The measured background was no greater than 10% of the total number of counts in the detector.

Control measurements and evaluations showed that the total effect of neutron scattering by the air, collimator walls, and chamber was no greater than 5% and hardly altered the neutron spectra.

Figure 3 shows the energy spectra of neutrons formed by 14-Mev neutrons passing through 2.7 cm of U^{235} (about $\lambda_{in}/3$), 2.5 cm (about $\lambda_{in}/3$) and 8 cm (about λ_{in}) of U^{238}. In treating the results, we took account of the dependence of the detector efficiency on neutron energy; no correction for the resolving power of the spectrometer was introduced. The lowest limit of energy measured was about 40 kev, due to the decrease of the number of counts in the channels to the background level. For neutron energies below 100 kev the data for several channels was united.

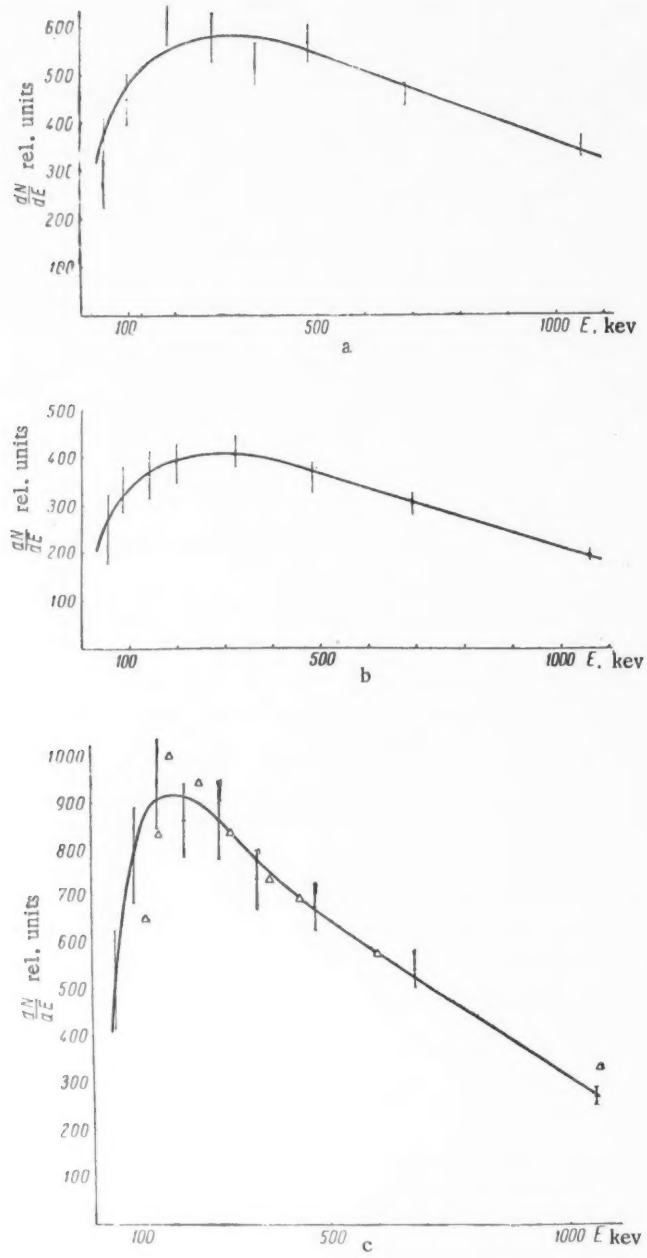

Fig. 3. The spectra formed by 14-Mev neutrons passing through thicknesses of uranium. a) 2.7 cm of U^{235}; b) 2.5 cm of U^{238}; c) 8 cm of U^{238}. The spectra normalized to a common primary neutron flux. The points labeled Δ are those obtained from proportional-counter measurements [2].

The spectra shown in Figs. 3a and b result essentially from single inelastic interactions between the 14-Mev neutrons and uranium nuclei. The fundamental neutron-producing process in the energy region investigated involves the evaporation of neutrons from the excited compound nucleus [3]. The results obtained for energies greater than 0.2 Mev are in agreement with this assumption, although for energies less than 0.2 Mev the number of neutrons obtained is somewhat higher than that given by the expression $E \cdot \exp(-E/T)$ describing neutron evaporation. This can be explained both by multiple inelastic collisions within the uranium and by neutrons from the (n, 3n) reaction. The influence of each of these factors will be clarified presently.

When the 14-Mev neutrons pass through the 8 cm layer of U^{238} (Fig. 3c), there occurs a large number of low-energy neutrons. This is a result of multiple inelastic collisions and verifies the presence of low-lying levels in the U^{238} nucleus.

We hope in the future to increase the efficiency of the method by reducing the background of scattered neutrons and to continue the measurements of neutron spectra produced by the passage of 14-Mev neutrons through various substances.

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OBSERVATION OF TRACKS OF CHARGED PARTICLES IN A MIXTURE OF ALCOHOL AND WATER VAPORS

Iu. L. Sokolov

In the course of studying the formation of tracks of charged particles in a diffusion chamber it was suggested that even in those cases where supersaturation was absent there would occur along the trajectory of the particle for some reason or other optical inhomogeneities which would cause scattering of light. Naturally, the transverse dimensions of such inhomogeneities would be extremely small and hence, in practice the light scattered by them would be propagated only in a forward direction within a very small solid angle.

Fig. 1. Diagram of apparatus. 1) Light source; 2) condenser; 3) diaphragm; 4) long-focus lens; 5) shutter cutting out the image of the diaphragm visible in the focal plane of the lens; 6) telescope for observing the working volume situated close to the lens (bounded by dotted line).

An attempt was made to observe such inhomogeneities by illuminating the working volume of a chamber containing saturated vapor by the dark-field method proposed by Tepler. If certain conditions are fulfilled, this method permits the registration of light deflected from the original direction at angles of the order of a fraction of a minute (Fig. 1).

Figure 2 shows a photograph of α-particle tracks from polonium, obtained by the author using this arrangement. The working volume of the chamber was filled with air with the addition of saturated vapors of alcohol and water at a pressure of 2 atmos and a temperature +7°C. Illumination was provided by a 1 kw mercury capillary lamp SVD with a luminous flux of about 60,000 lumens. The chamber operated constantly, the track images appearing in the field of view for an extremely short time.

A variant of the continuous action chamber described above is a chamber the working volume of which contains a liquid in a state close to the critical state.

It should be noted that, because of the necessity of using very powerful lamps, the construction of the chambers described involved serious difficulties connected with the removal of stray light. These difficulties are particularly obvious in operating a chamber containing a "critical liquid." In this case, when the author was observing light emitted from the working volume at angles up to 1° he could not obtain a dark field on account of the intense diffusion light which was seen on approach to the critical point. This light most probably arose from fluctuations of the refractive index (and possibly also from scattering on embryo bubbles) which occur in a liquid in a dynamically unstable state. Therefore, for the practical realization of a continuous action chamber containing a "critical liquid" it is essential to ascertain whether such conditions can be obtained which will allow the observation of particle tracks at considerably greater angles of light scattering.

The results obtained in experiments with the chamber filled with condensing vapors do not permit definite conclusions on the nature of the optical inhomogeneities produced by the charged particles. It is quite probable that the light scattering in this case is due to embryo drops formed on ions since it is known that charged drops can form in a saturated and even in an unsaturated volume. In any case we may assume that in the strongly disturbed region close to the trajectory of the charged particle there occur short-lived and rapidly decaying processes of formation of embryo drops. Later these drops evaporate since their further growth is impossible because of the absence of supersaturation in the working volume.

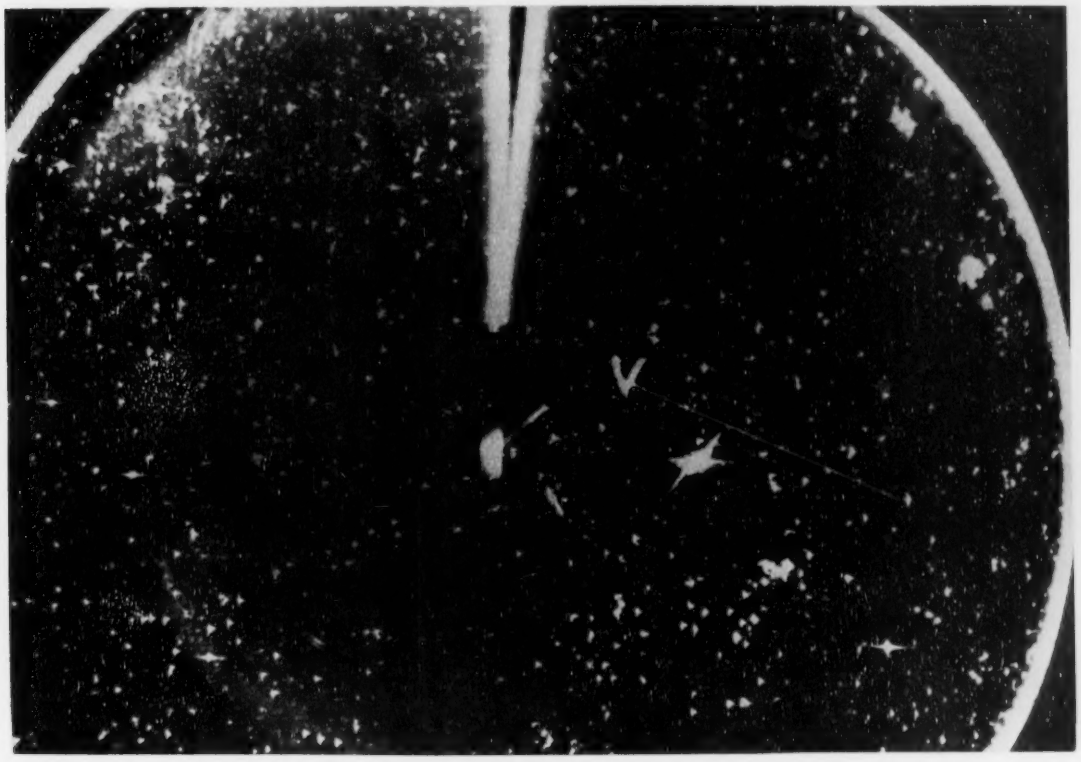

Fig. 2. Tracks of α-particles from polonium.

In the opinion of E. K. Zavoiskii, in certain conditions a substantial role in the formation of optical inhomogeneities is taken by the shock wave formed as a result of the rapid evolution of energy in the small volume along the trajectory of the particle. If such a hypothesis is correct, then with the illumination of the working volume by the Tepler method it may be possible to observe particle tracks in noncondensing gases (which can be compressed to pressures of several hundreds of atmospheres) and, what is more probable, in liquids and solid bodies. The light scattering in chambers of such type will occur on the compressions produced by the shock waves.

It should be noted that, although the mechanism of the formation of optical inhomogeneities is still obscure, experiments with a chamber filled with condensing vapors have given very valuable results since it has proved that it is possible to observe directly the tracks of charged particles in an atmosphere of saturated vapor. Chambers constructed on such a principle should possess time-constant sensitivity and continuity of action.

The author conveys his deep gratitude to Prof. E. K. Zavoiskii for valuable advice and suggestions.

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YIELDS OF CERTAIN HEAVY FRAGMENTS IN THE FISSION OF U^{233}

R. N. Ivanov, V. K. Gorshkov, M. P. Anikina, G. M. Kukavadze, and B. V. Ershler

The present work is a continuation of the work on the determination by mass spectrometry of the absolute yields of certain rare-earth elements formed in the fission of U^{233}, a report of which was given at the Session of AN SSSR on the Peaceful Uses of Atomic Energy in July 1955 [1]. The investigation was conducted on a U^{233} specimen described in works [1] and [2]. In order to obtain the most reliable data the absolute yields of the fission products were determined by the method of isotopic dilution [3] and by the integral mass spectrographic method of concentration determination [4].

Element	Mass number	Isotope composition: Data of isotopic dilution method: fission fragments	Isotope composition: Data of isotopic dilution method: mixture of natural elements with fragments *	Isotope composition: Data of integral mass spectrographic method: fission fragments	Absolute fission yields, %: Data of isotopic dilution method	Absolute fission yields, %: Data of integral mass spectrographic method
Cs	133	1**	1	1	5.20±0.30	5.50±0.13
	135	0.13±0.01	0.058±0.002	0.17±0.02	—	—
	137	1.037±0.003	0.46±0.007	1.032±0.008	5.80±0.30***	6.16±0.14***
Ce	140	0.99±0.03	3.52±0.05	1.014±0.007	5.45±0.50	6.16±0.24
	142	1**	1	1	5.50±0.50	6.06±0.24
	144	≤0.02	—	≤0.007	—	—
Nd	143	2.21±0.03	1.29±0.01	2.35±0.03	5.00±0.30****	5.19±0.17****
	144	1.89±0.05	1.59±0.02	1.92±0.01	3.80±0.40****	3.84±0.15****
	145	1.29±0.02	0.80±0.008	1.30±0.008	2.82±0.25	2.88±0.08
	146	1**	1	1	2.20±0.15	2.24±0.07
	148	0.47±0.01	0.39±0.006	0.48±0.01	1.03±0.10	1.07±0.04
	150	0.23±0.02	0.28±0.006	0.22±0.005	0.51±0.08	0.49±0.02
Sm	149	0.085±0.003	0.42±0.003	≤0.093	0.66±0.13	0.70±0.03
	150	1.25±0.20	0.52±0.01	1.50±0.05	—	—
	151	0.24±0.03	0.06±0.005	0.25±0.01	Sum	0.54±0.03
	152	1**	1	1	0.60±0.14	
	154	≤0.10	—	≤0.093	—	—

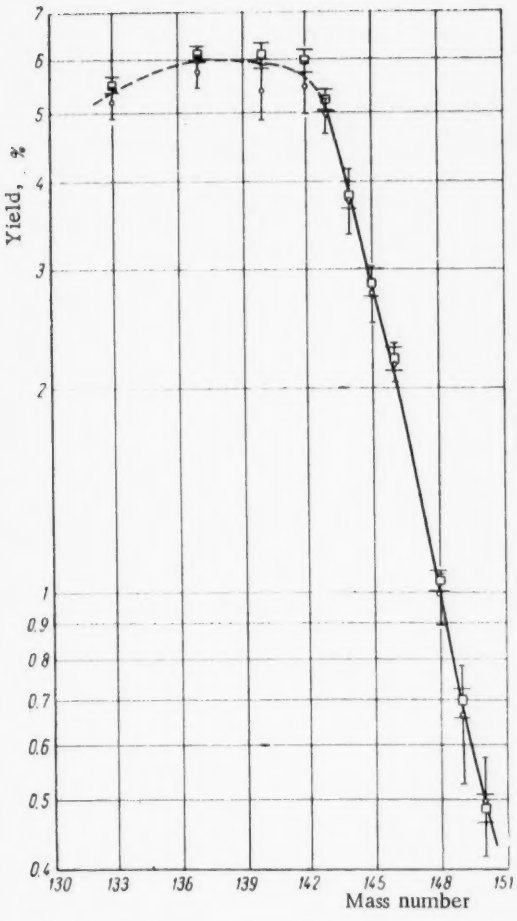
* In the calculation for the total quantity of fragments (11.9±0.2 mg) the quantity of natural cesium in the mixture was 0.44 mg, cerium – 2 mg, neodymium – 1.39 mg and samarium – 0.42 mg.

** Here and later the yield of the given isotope is taken as unity.

*** The data are given with a correction for β-decay ($T_{1/2}$ = 33 years).

**** The data are given with a correction for the reaction $Nd^{143}(n, \gamma)Nd^{144}$ (σ_a = 280 barns).

The U^{233} specimen was irradiated by thermal neutrons in a nuclear reactor for more than two months. After irradiation the uranium along with the platinum and aluminium casings and lead envelope was dissolved in aqua regia.



Dependence of absolute yields of fission products on mass number. ⊡ Yield values determined by integral mass spectrography; ⊹ yield values determined by isotopic dilution.

In the first method of measurement cerium, neodymium and samarium were separated from the specimen with the help of an yttrium carrier, and cesium with a potassium carrier. The fission products separated by this method were analyzed on a mass spectrometer of "MS" type. In the second case the investigated rare-earth elements were analyzed on a 60° mass spectrograph with radius of curvature of the main ion trajectory 12.5 cm. Chemical fractionation was not carried out, i. e., the analyzed specimen contained almost all the fission products, undisintegrated U^{233}, and also a considerable quantity of platinum, aluminum and lead.

In both methods we used a two-filament surface ionization source [4, 5].

The table gives results of measurements and calculations obtained by the method of isotopic dilution and integral mass spectrography.

As may be seen from the table, the values of the absolute yields of fission products, obtained by the two different methods, are in substantial agreement within the limits of measuremental error.

From the results of measurement a curve of the absolute yields of the fission products against mass number was plotted (see figure). Because of the absence of certain points in the present work the upper part of the curve is given by a broken line. This region of mass has been studied in more detail in [6].

It is essential to note that in the present work the yield of the isotope with mass number 144 has been made more accurate than the yield reported earlier in work [1].

The table only gives the sum of the yields of Sm^{151} and Sm^{152}. To obtain separately the absolute yields of these isotopes on the basis of the deduced data is difficult since the absorption cross section of Sm^{151} is not known accurately.

The isotope Sm^{150} was formed as a result of burn-up of Sm^{149} in the reaction $Sm^{149}(n, \gamma)Sm^{150}$. Therefore, the yield of element with mass number 149 is calculated as the sum of the quantity of isotopes Sm^{149} and Sm^{150} in the specimen.

Using the formulas for the number of atoms of Sm^{149} and Sm^{150} at the time of measurement [7] it is possible to determine the absorption cross section for thermal neutrons of Sm^{149}. The value obtained is $\sigma_{149} = 49{,}000 \pm 8000$ barns which is in good agreement with results in the literature [8].

Finally, it is possible to evaluate the absorption cross section of Xe^{135} from the yield curve, quantity of Cs^{135} and half-life of Xe^{135}.

Bearing in mind that Cs^{135} is formed from Xe^{135} in the following manner:

$$Xe^{135} \xrightarrow[9.2\ \text{hrs}]{\substack{n,\gamma \\ \beta^-}} \begin{cases} Xe^{136} & (\text{stable}) \\ Cs^{135} & (2.6 \cdot 10^6\ \text{yrs}), \end{cases}$$

it is possible to compile a system of equations:

$$\frac{dN_{Cs}(t)}{dt} = N_{Xe}(t)\,\lambda_{135},$$

$$\frac{dN_{Xe}(t)}{dt} = N_U \sigma_U f_{135} \Phi - N_{Xe}(t)\,\sigma_{135}\Phi - N_{Xe}(t)\,\lambda_{135}$$

where N_{Cs} is the number of Cs^{135} atoms; N_{Xe} is the number of Xe^{135} atoms; N_U is the number of uranium atoms; σ_U is the absorption cross section for thermal neutrons of U^{233}; Φ is the neutron flux; f_{135} is the absolute yield of Xe^{135} *; σ_{135} is the absorption cross section for thermal neutrons of Xe^{135}; λ_{135} is the decay constant of Xe^{135}.

Solving this system of equations for N_{Cs}, it is possible to obtain the value of $\sigma_{135} = (3.2 \pm 1.0) \cdot 10^6$ barns, which also agrees well with literary data [8].

In conclusion the authors consider it their duty to express their thanks to L. L. Gol'din for discussion of the results.

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* Determined by interpolation of yield curve in the region of mass numbers 134-136.

THE SPECTRAL ANALYSIS OF SMALL SAMPLES OF ACTINIUM

N. I. Kaliteevskii and A. N. Razumovskii

Only in recent years have amounts of actinium sufficient for the detailed study of the chief properties of this element become available to experimenters and, therefore, the necessity has arisen for developing methods of the spectral analysis of actinium preparations containing other elements [1, 2].

Actinium is characterized by considerable α- and β-activity. The γ-activity of actinium preparations, in equilibrium with the decay products, is relatively small. This makes it necessary to exercise great care in hermetically sealing the volume in which the light source is situated, but eliminates the necessity of using chambers of lead glass or lead bricks to absorb the γ-rays.

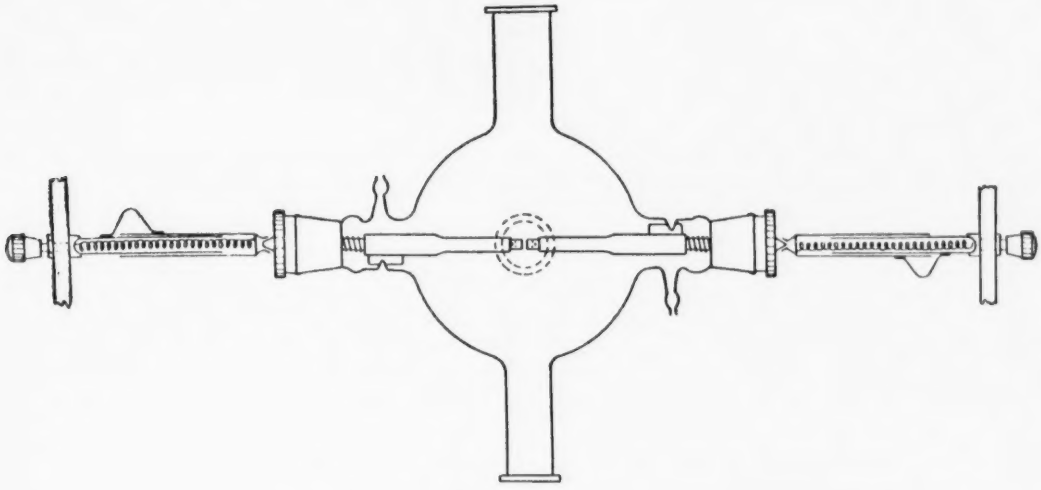

Fig. 1: Flask for exciting the spectrum of radioactive preparations.

In our experiments, the actinium spectrum was excited in a glass flask with three branch attachments serving as windows, closed by plates of fused quartz (Fig. 1). After the introduction of metal slides, with electrode holders on their ends, the flask was in contact with the outside air only through two branch pieces to which rubber hoses were attached. One of the hoses was connected to a carbon dioxide cylinder and the other served as outlet for the gas through a special absorber into the ventilation system. The flask was fixed inside a protecting glass chamber made from organic glass, also hermetically sealed in a suitable way (Fig. 2). Before the spectrum of the sample was photographed, the flask was flushed with carbon dioxide gas and the spectrum was excited in a CO_2 atmosphere. This eliminated the appearance of CN lines and facilitated the spectral analysis for elements whose lines lie in the near ultraviolet. The conditions for the burning out of the sample were also somewhat changed. After exposure, before the electrodes were changed, a fresh quantity of gas was carefully passed through the flask.

TABLE 1

The Wavelengths of the Actinium Lines in the Ultraviolet Region of the Spectrum

Serial no.	Wavelength in A	Intensity on the 10-point scale	Remarks
1	2726.3	3	
2	2729.1	2	
3	2753.1	2	
4	2760.1	3	
5	2731.7	3	
6	2797.6	5	
7	2804.4	4	
8	2833.5	2	
9	2846.7	8	
10	2856.2	2	
11	2895.2	3	
12	2896.7	5	
13	2952.9	10	Spark line
14	2994.3	10	
15	3001.8	2	
16	3019.5	7	
17	3043.4	10	
18	3069.4	7	
19	3076.4	8	
20	3076.8	8	
21	3078.1	6	
22	3084.9	2	
23	3085.9	5	
24	3087.9	4	
25	3111.6	2	
26	3112.8	8	
27	3118.9	3	
28	3130.5	2	
29	3153.2	8	
30	3154.5	9	
31	3164.9	8	
32	3171.3	3	
33	3176.8	2	
34	3202.1	2	
35	3204.9	3	
36	3219.3	4	
37	3237.8	6	
38	3260.5	10	
39	3317.9	5	
40	3322.5	3	
41	3331.4	2	
42	3383.5	6	
43	3392.8	10	Spark line
44	3417.6	10	
45	3460.9	2	
46	3481.0	10	
47	3489.5	8	
48	3529.5	4	
49	3555.0	5	
50	3565.5	10	
51	3756.6	6	
52	3885.5	5	
53	3915.1	4	
54	4034.5	4	

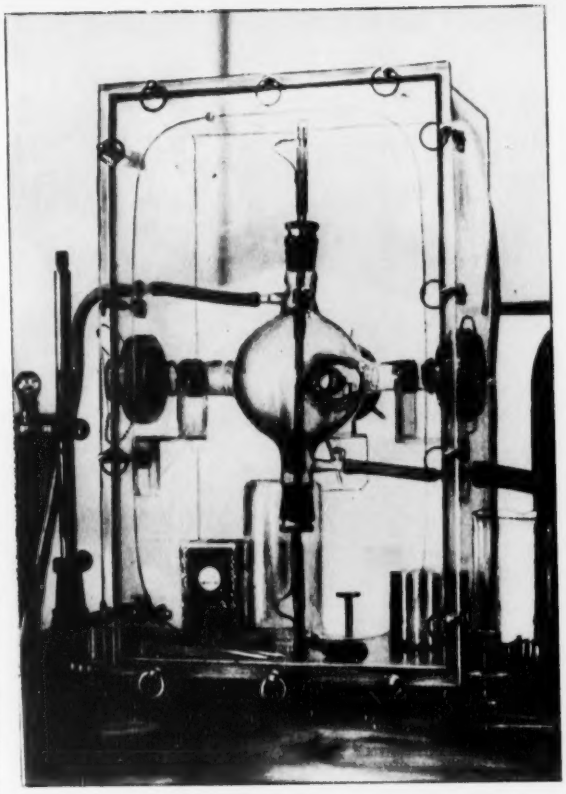

Fig. 2. The protecting chamber with the flask for exciting the spectrum of radioactive preparations.

About 0.15 mg of actinium, in the form of a solution of $AcCl_3$, was available for analysis. The actinium spectrum was excited by a condenser spark or an activated arc between copper or carbon electrodes, respectively. The sample solution was placed on the flat front surface and dried until a water-free residue was obtained.* A number of photographs of the spectrum were taken with samples containing from 15 to 30 μ of actinium. When the analysis was made with the arc, the sample was fixed on the upper layer of the carbon electrode. For this, the method of the partial destruction of the polystyrene protecting film by sulfuric acid was used with the introduction into the sample of relatively large amounts of sodium to stabilize the burning of the arc [4]. In view of the fact that in doing this it is not possible to determine the presence of sodium in the sample investigated, the analysis for sodium was carried out in the other experiment where the solution is applied to the copper electrodes and the spectrum is excited by a condenser spark.

* The solution of salts of elements with a high activity reacts very strongly with glass. Therefore, it is necessary to apply the solution onto the electrodes for spectral analysis immediately after it is prepared. If the solution remains in a glass vessel for several hours, the sample will be found to be contaiminated by boron, silicon and calcium.

The spectrum of a sample was simultaneously photographed by three spectroscopic instruments, which can always be recommended for spectral analysis involving small quantities of material. The ultraviolet part of the spectrum was photographed with the spectrograph Q-24, the visible part with the ISP-51 spectrograph having a camera with a focal length of 270 mm. The third spectrograph (KS-55) had a glass optical system and the spectrum was photographed in the region 3700-5000 A.

The adjustment of the optical system was carried out by means of the shadow projection of the electrodes and was facilitated by the fact that the horizontal displacement of the electrodes was eliminated, while the height adjustment could be made, with the flask closed by rotating the knobs on the slides. The condenser lenses were placed outside the protecting chamber; the geometrical dimensions of the flask and chamber were chosen to suit the luminosity of the spectrographs. The exposure in the condenser spark was for 5 sec, and in the arc for 10 sec. One of the experiments for the rough study of the actinium spectrum consisted of exciting the spectrum of the sample by alternate short (1-2 sec) exposures with the arc and with the spark, so that it would be possible to distinguish the arc and spark lines.

Semi-quantitative spectral analysis of actinium preparations was carried out with the help of standard mixtures, using as the main component an element which is similar to actinium, namely lanthanum, which was introduced into the standard solutions in the same concentration, as the sample analyzed contained actinium. For the analysis, those lines were used on which neither actinium nor lanthanum lines were superimposed. It was assumed that suppression of the lines of the sample by actinium and lanthanum lines will be of the same order of magnitude. In the analysis of very small samples (15-30 μg) this assumption is undoubtedly valid. Since the actinium preparation investigated does not contain gallium, gallium was used as an internal standard in further experiments, for which a definite quantity of $GaCl_2$ solution was placed on the electrodes.

In developing the method of analysis it was desirable to measure the wavelengths of the most intense actinium lines in the ultraviolet region of the spectrum.* The results of these measurements are given in Table 1. As was to be expected, actinium, which precedes a series of actinides (just as lanthanum precedes a series of lanthanides), has a meager spectrum by comparison with the other members of this series. As in the lanthanum spectrum, we observe individual lines of high intensity, which is often not so in the spectra of the other lanthanides and actinides (praseodymium, uranium). The ultraviolet region of the spectrum was photographed using an instrument of small dispersion and, therefore, the wavelengths were measured with an error of 0.1-0.2 A, which is completely adequate for the analysis of actinium.

The actinium preparation investigated was analyzed for the presence of boron, aluminum, calcium, magnesium, manganese, barium, lead, sodium, iron and silicon. The main lines used are given in Table 2. The sensitivity of the analysis for the majority of the elements indicated reached ~ 0.1%, but some of the impurities, for example, manganese, even using very small samples (15-30 μg) could be determined in concentrations as small as ~ 0.03%.

TABLE 2

The Spectral Lines of the Impurity Elements and of the Reference Element Gallium (in A)

B	I 2496.8	Pb	I 4057.8
Al	I 3092.7	Na	I 5889.9
Ca	II 3933.7	Fe	II 2382.0
Mg	I 2852.1	Si	I 2881.6
Mn	II 2576.1	Ga	I 2943.6
Ba	II 4554.0		

The question whether the evaporation method [5, 6] can be applied to the analysis of actinium preparations so as to increase the sensitivity of the determination remains open because of the absence of data on the volatility of Ac_2O_3 in vacuum and in the atmosphere, and to clarify this question a direct experimental verification is necessary.

The authors are grateful to A. N. Zaidel, D. M. Ziv, N. S. Shimanskaia and E. A. Iashugina for valuable advice and help during the present work.

* The actinium spectrum was investigated in 1951 by Meggers et al. [3]. In the brief report the authors indicated that they had investigated a large number of actinium lines, but as yet only the wavelengths of 10 lines in the visible part of the spectrum have been published. Now published in the July issue of J. Res. Nat. Bur. Stand. 58, 297 (1957) (Editor's note).

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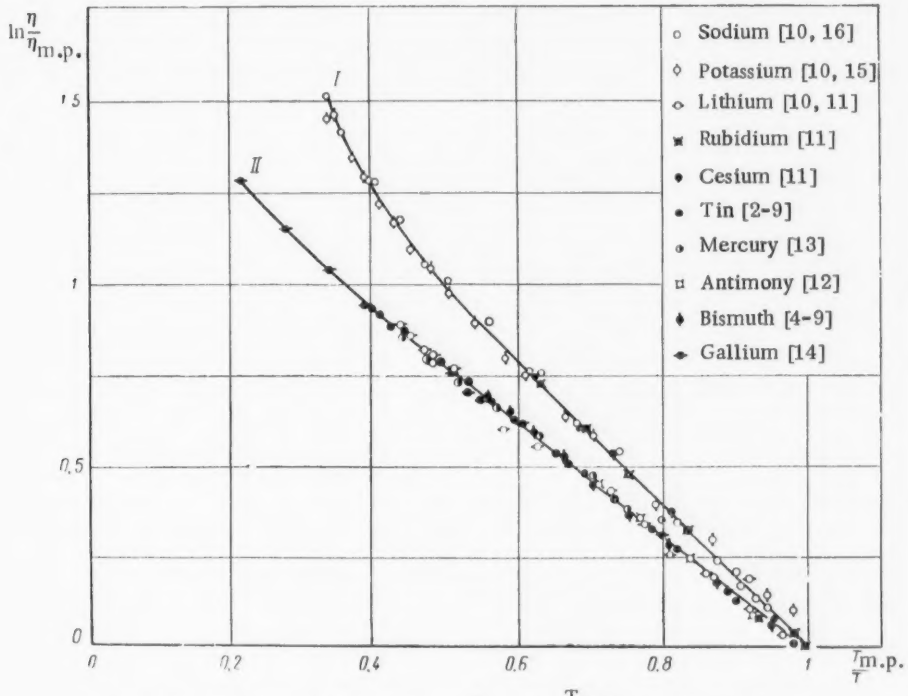
THERMODYNAMIC SIMILARITY AND VISCOSITY OF MOLTEN METALS

A. N. Solov'ev

From the theory of thermodynamic similarity it follows that, for a group of thermodynamically similar elements, the dependence of certain physical properties (heat of evaporation, viscosity, surface tension, compressibility, thermal conductivity, etc.) on the parameters of state can be expressed as a universal function of these parameters. I. I. Novikov [1] has obtained the following expression for viscosity:

$$\eta = \left(\frac{\mu}{g}\right)^{1/2} \frac{P_{cr}^{2/3}}{R^{1/6} T_{cr}^{1/6}} \cdot f\left(\pi, \tau, \frac{c_{r0}}{R}\right),$$

where $\pi = P/P_{cr}$ and $\tau = T/T_{cr}$ are the parameters of state, μ = the molecular weight, R = the universal gas constant, P_{cr} and T_{cr} are the critical pressure and temperature and g = the acceleration due to gravity.



Graph of the relationship between $\frac{\eta}{\eta_{m.p.}}$ and $\frac{T_{m.p.}}{T}$ for molten metals.

Since the viscosity of liquids depends to only a small extent on pressure, by using the well-known approximation it is possible to write:

$$\eta = c \cdot f_1\left(\frac{T}{T_{cr}}\right).$$

From this formula it follows that, knowing the critical parameters of each element of a group of thermodynamically similar elements and knowing also the form of the function (for one element of the group), it is possible to estimate the viscosity of any element of this group at any temperature. Conversely, having determined experimentally the dependence of viscosity on temperature, it is possible to distinguish, by using the relationship given above, a group of thermodynamically similar elements. This in turn makes it possible to find by calculation other physical properties of the elements concerned. The discovery of groups of thermodynamically similar elements is also very interesting from the point of view of the study of liquid structures.

We have attempted to distinguish groups of thermodynamically similar elements among simple monatomic liquids of molten metals by constructing a graph with coordinates $\ln(\eta/\eta_{m.p})$ and $T_{m.p.}/T$ on the basis of our own data and of data in the literature [2-16].

Data on the viscosity of copper, silver and zinc were not used, since only approximately one-tenth of the temperature range of the liquid state was covered by the experiments and only 3-4 points were known.

Data on the viscosity of lead were excluded because the results of various workers did not agree satisfactorily among themselves.

Since the critical parameters, in particular the critical temperature, for metals are unknown, the treatment of the experimental data was carried out in relation to the melting point, which practically coincides with the temperature of the triple point, which for elements of a similar crystal structure may be the corresponding temperature.

The viscosity of the majority of metals has been measured over only a small temperature range. To extend this range semi-log coordinates have been employed. In addition these coordinates are more reliable for determining $\eta_{m.p.}$ (the viscosity at the melting point) by extrapolation of the viscosity curves to the melting point, since the majority of liquids obey the exponential law well in the vicinity of the melting point, whereas the experimental data of the various workers do not agree well among themselves in this region on account both of inaccuracy of the experiments and of supercooling.

From the graph it is clear that the experimental points are grouped around two curves with deviations at the melting point. Into the first group fall the alkali metals, with the exception of lithium, and into the second all the others.

Unfortunately, it is at present difficult to carry out a similar analysis for other properties of liquid metals (owing to the absence of reliable experimental data) in order to confirm such a grouping. However, it may be noted that the distribution of the elements into groups coincides with their distribution according to the groups of Mendeleev's periodic system. In the left-hand subgroups elements predominate which have unorientated metallic bonds and which form lattices approximating to close packing. The right-hand subgroups are occupied predominantly by elements which form complex structures. A similar comparison with respect to crystal structure gave the same result, since the state of ordering determined in the three-dimensional distribution of the molecules is preserved to a considerable extent in the liquid [17]. Thus the division into groups on the basis of crystallochemical data coincides in general with the division into groups based on viscometric data, and in this way the fundamental connection between the viscosity and the molecular structure of a liquid is confirmed.

It is possible to calculate the viscosity of any metal within a group at any temperature, knowing only the viscosity and temperature at the melting point.

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June 17, 1957

SCIENTIFIC AND TECHNICAL NEWS

RADIOACTIVE METHODS FOR THE CONTROL AND REGULATION OF INDUSTRIAL PROCESSES

From September 4th to the 7th, 1957, a scientific-technological conference was held in Riga dealing with the radioactive methods for the control and regulation of industrial processes, convened by the Chief Committee on the Peaceful Uses of Atomic Energy within the Soviet Council of Ministers, the Council for National Economy and the Academy of Sciences of the Latvian SSR and the Central Administration of the A. S. Popov Scientific-Technological Society for Radio Technology and Communication.

The Conference was opened by Active Member of the Academy of Sciences, Latvian SSR, K. K. Plaude.

There were two trends in the proceedings of the Conference: theoretical investigations of the design and construction of the devices based on the use of radioisotopes and the practical use of these devices in the various branches of the national economy.

A review paper, presented by Doctor of Technical Sciences Prof. N. N. Shumilovskii and Candidate of Technical Sciences L. V. Meltser, surveyed the results of work by Soviet scientists and industrial designers on the construction and the application, in science and industry, of devices based on the use of radioisotopes for the control and regulation of technological processes.

On behalf of the group of associates of the Institute of Physics, AN Latvian SSR and of the Tallin Measuring-Instrument Factory, LSSR Worker of Merit in Science and Technology, engineer A. T. Kundzin'sh reported on the results of work on the construction of a series of standard electronic units for automatic instruments of the relay type. The construction of standard units enables them to be used as standard elements in designing instruments for various applications. Examples of standard units were demonstrated at the Conference. The Tallin Measuring-Instrument Factory will start mass producing such units in the near future.

An interesting report on the method of eliminating errors arising from the instability of radiation detectors and electronic circuits was made by an engineer of the AN SSSR Physics Institute, B. I. Verkhovskii. This method, which enables the accuracy of radiation measurements to be considerably increased, consists in irradiating the detector using a standard source at the same time as the radiation flux to be measured falls on the detector. The total signal produced is transformed by the detector circuit, as the result of which the magnitude of the measured flux is obtained which does not depend on variations in the circuit and detector parameters.

A comprehensive report on the topic: "On the statistics of the control signal in registering radiation by a radioactive relay" was given by the Scientific Associates of the AN LSSR Taksar Physics Institute and V. A. Ianushovskii.

The theoretical bases for designing level and density indicators were discussed in the report of engineers G. G. Iordan and K. S. Furman (Scientific Research Institute of Heat Instrumentation).

A number of papers and communications were devoted to new methods for registering ionizing radiation and to new instruments designed for this purpose.

Engineers I. D. Konozenko and V. I. Ustianov (AN Ukrainian SSR Physics Institute) have developed techniques for the manufacture of vacuum mono- and polycrystalline sulfur-cadmium detectors of γ-radiation with a sensitivity of $5 \cdot 10^{-3}$ to 10^{-2} $\mu amp/\mu r \cdot sec$, also mosaic-type detectors with a sensitivity of up to 10^{-2} $\mu amp/\mu r \cdot sec$, and have carried out a wide study of the various parameters of sulfur-cadmium detectors (stability of sensitivity, volt-ampere, dosimetric and relaxation characteristics, etc.).

Engineer A.A. Arkhangel'skii and Corresponding Member of the AN Ukrainian SSR G. D. Latyshev (Leningrad Institute of Railway Transport) reported on the results of tests on new types of electron multipliers, developed by various organizations.

In a paper presented by the Chief Committee on the Peaceful Uses of Atomic Energy within the USSR Council of Ministers the main principles for the organization and development of laboratories for work with radioisotopes were discussed and standard plans were demonstrated for laboratories designed for work with shielded and unshielded sources of radiation activities. On the basis of these principles plans have already been developed, or are being developed, for standard laboratories for work with radioisotopes in the various branches of the national economy.

Engineer L. S. Eig reported on new self-quenching and nonself-quenching halogen counters for registering high-intensity radiation. These counters have practically unlimited lifetimes, small dimensions and their readings are almost temperature independent. However, they are unsuitable for accurate measurements as they do not have a proportional region and their characteristics depend on the voltage.

A. A. Akhromenkov, engineer of the All-Union Scientific Research Institute for Oil and Gas Processing and the Production of Synthetic Liquid Fuel, on behalf of a group of authors reported on the industrial tests of γ-densitometers that have been carried out. The use of these instruments enables a rapid and accurate determination to be made of the boundaries between various petroleum products successively pumped through a pipeline, permits each of them to be directed automatically into the proper reservoirs and to a large extent eliminates the mixing of petroleum products, which at the present time leads to a lowering in quality and additional distilling.

Engineer Iu. S. Zaslavskii and others reported on a new instrument for maintaining the level of phase division in oil-processing installations. The instrument has been tested successfully in a cracking installation.

Engineers V. K. Latyshev and V. V. Lyndin of the Central Scientific Research Institute for Ferrous Metallurgy reported on a system, developed by a group of authors, for the automatic regulation of the level of liquid metal in a crystallizer with continuous pouring and on the method for stabilizing the regulating process. The use of these systems for the continuous casting of pipes at the 1st of May Factory in Kalinin and at the Sinarsk Pipe Factory has increased the production of pipes by 40-50% and has considerably simplified the work of the operators.

The Chief Engineer of the Tallin Measuring-Instrument Factory, K. K. Shpor, V. E. Banashek and others reported on the methods developed by them for automatically regulating the density of a liquid. A radioisotope is introduced into the hydrometer, the radiation is registered by a radioactive relay with a halogen counter connected to a circuit regulating the industrial process and making it automatic. When the density changes, this circuit reacts on the appropriate mechanism and restores the set density. This method can be used in the food, chemical and other branches of industry.

V. E. Banashek, Chief Engineer of the Riga Factory "Dzintari," gave a report, on behalf of a group of authors, on devices for measuring out liquids based on the attenuation of γ-rays by the surface layer of a liquid. The report presents the advantages of this method as compared with the other known methods for measuring liquid levels. The weighing of loose material can be made using a contactless method by registering the position of the balance pointer.

An extensive study has been carried out by the collective of the Factory "Red Metal Worker" (Konotop) on the use of γ-relays for making the processes in the coal industry automatic. In the report (presented by Engineer A. V. Chashchinov of the factory) a description is given of the γ-relays manufactured by the factory, which contain crystal triodes working on alternating current.

More than 400 delegates took part in the Conference and more than 30 reports were presented.

P. S., N. L.

IN THE PHYSICS INSTITUTE OF THE UKRAINIAN SSR ACADEMY OF SCIENCES

The AN Ukrainian SSR Physics Institute was established in 1929. At the present time, research is being carried out in nuclear, molecular, theoretical and semiconductor physics, electronics and spectroscopy.

The nuclear-physics section, headed by Prof. M. V. Pasechnik, is working on the investigation of the interaction of neutrons and charged particles with nuclei. This work is being carried out using an electrostatic 2.5 Mev accelerator, a cyclotron producing deuterons with an energy of 16 Mev and low-voltage neutron generators. A considerable part of the detecting instruments was developed and constructed in the Institute: spherical ionization chambers for neutron detection, scintillation γ-spectrometers, multi-channel amplitude and time-of-flight analyzers, etc.

The main investigations in neutron physics were described in M. V. Pasechnik's report at the Geneva Conference on the Peaceful Uses of Atomic Energy in 1955. Since then, similar measurements have been continued using an improved apparatus and new research has been carried out. For example, M. V. Pasechnik, I. V. Barchuk and Iu. A. Tsibul'ko have carried out measurements on the energy of γ-rays emitted by nuclei after inelastic neutron scattering. V. I. Strizhak has measured the cross section for the reaction (n, 2n).

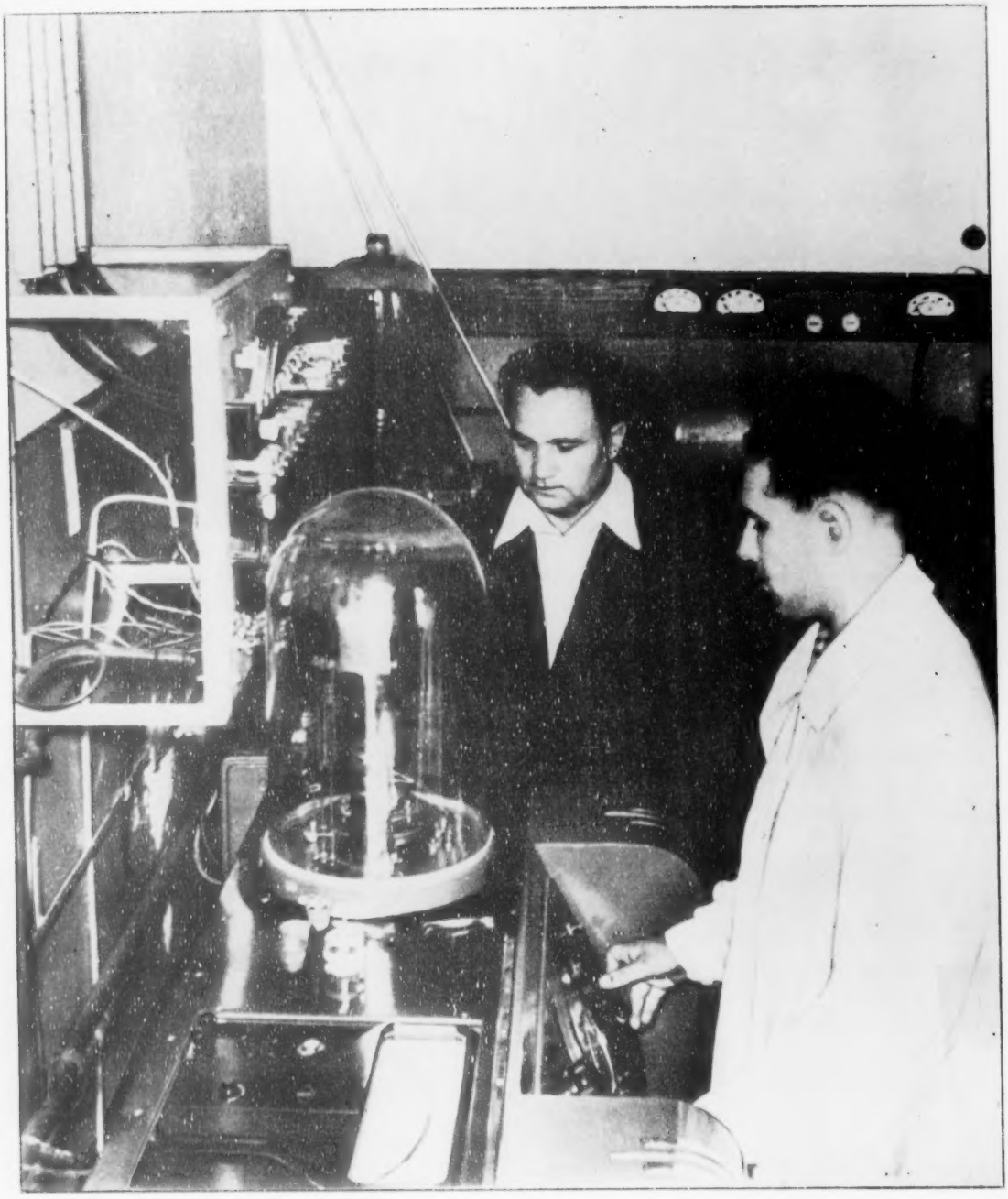
At the cyclotron, work is being carried out for studying the angular distribution of elastically-scattered protons and protons from the reaction (d, p). This work was only started this year and is estimated to take several years. At the cyclotron, artificial radioisotopes are also produced which are used in science and technology.

Radioisotopes are widely used in all sections of the Institute. In the semiconductor section, headed by Academician V. E. Lashkarev, AN Ukrainian SSR, investigations were carried out using radioisotopes for the study of the influence of impurity concentrations on the semiconductor properties. Here also the action of radiation on semiconductors is being studied as well as a number of other investigations.

The use of radioisotopes in the physical-electronics section enabled a number of investigations on the evaporation of cathodes to be carried out. This section is headed by Corresponding Member of the AN Ukrainian SSR N. D. Morgulis.

In 1956 the workers of the Institute took part in ten All-Union and one International Conferences (in Amsterdam); 41 reports were presented. In the same year, 80 papers were published by associates of the Institute, while 87 have been submitted for publication in 1957.

V. Parkhit'ko

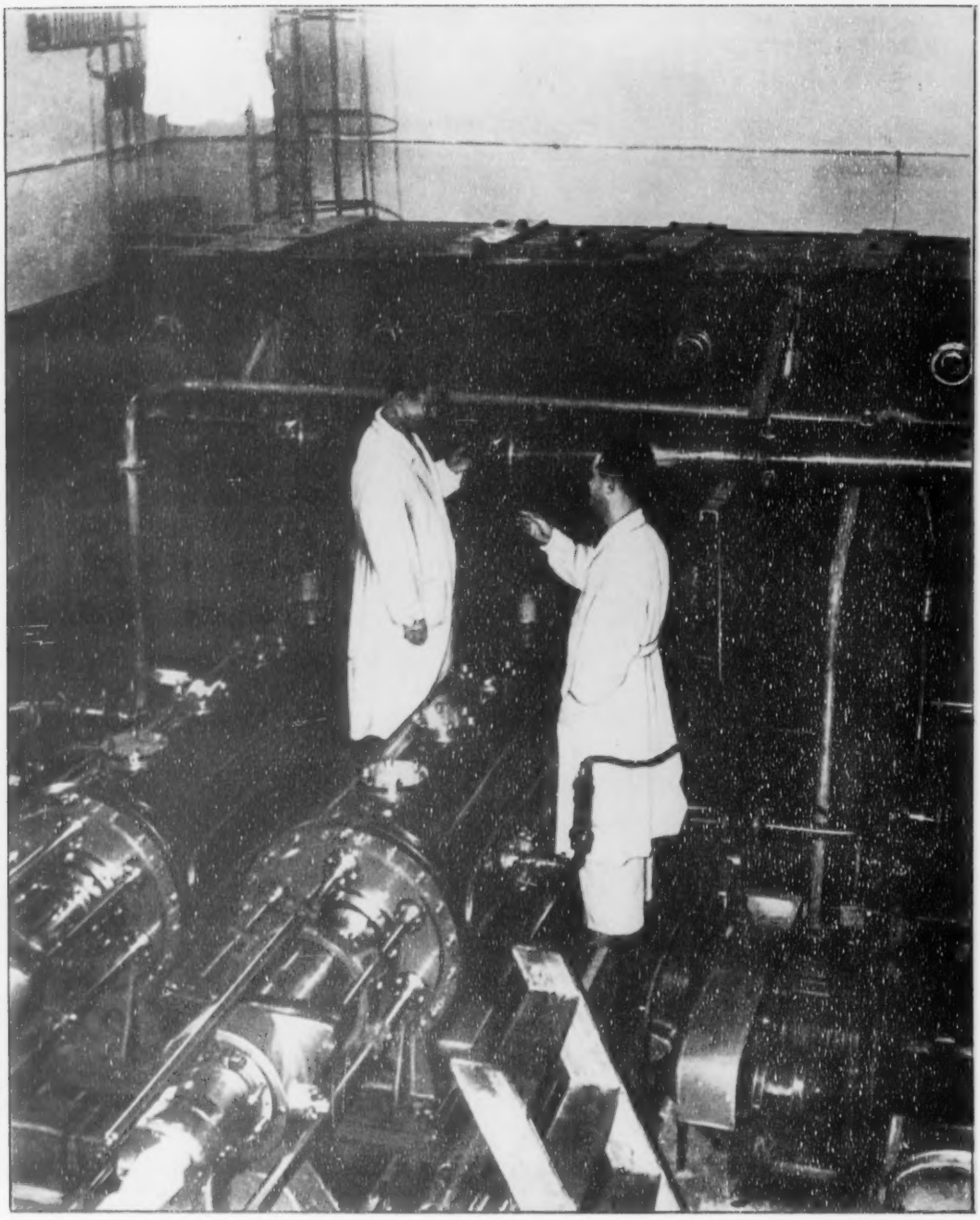


Candidate of Physico-Mathematical Sciences E. G. Meseliuk (left) and laboratory technician V. S. Khudolii carry out observations at equipment for growing semiconducting single crystals.

Photograph: V. Parkhit'ko

In the control room of the cyclotron of the AN Ukrainian SSR Physics Institute. The Chief Engineer of the cyclotron laboratory, V. A. Kovtun, is in the foreground.

Photograph: V. Parkhit'ko



An inspection of the supply lines of the cyclotron is being carried out by Engineers V. A. Golobordko and V. A. Pashin.

Photograph: V. Parkhitko

NEW ITEMS IN THE PAVILION "THE USES OF ATOMIC ENERGY FOR PEACEFUL PURPOSES" OF THE ALL-UNION INDUSTRIAL EXHIBITION

For the second year the All-Union Industrial Exhibition is open in Moscow. And for the second year the biggest attraction is the pavilion: "The Uses of Atomic Energy for Peaceful Purposes."

By comparison with those of last year, the exhibits of the section have changed considerably; new sections have appeared and the method of presentation has changed. In the section "The Physics of the Atomic Nucleus," which introduces the problem of attaining thermonuclear reactions, the model of the atom, the elementary particles and their transformations have been presented more successfully. Here also are presented models and diagrams of the various types of accelerators from the electrostatic generator EG-2, 5P to the most powerful proton synchrotron in the world, accelerating protons to an energy of 10 Bev, and also a large number of various instruments required for research in the field of nuclear physics.

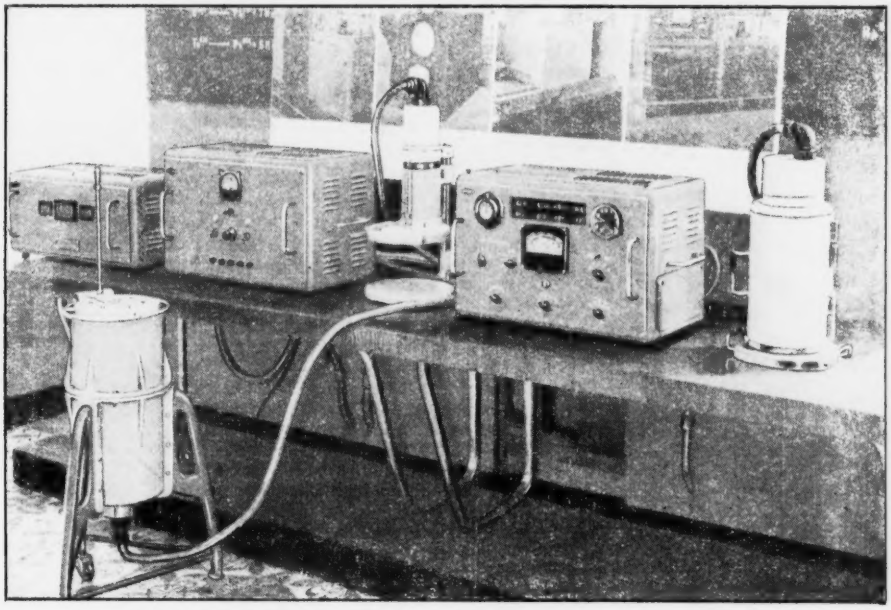


Fig. 1. The laboratory scintillation analyzer LAS.

The display in the section "Atomic Raw Materials" is also considerably different from that of last year. Deserving notice is the aero-geophysical equipment ASG-38, with a scintillation γ-radiometer and analyzer, with which the occurrence of uranium and thorium ores can be distinguished; the laboratory scintillation analyzer LAS (Fig. 1), which is intended for the qualitative and quantitative analyses of radioactive-ore samples and for the determination of the absolute and relative uranium and thorium content of ores; the field radiometer SG-42, incorporating a scintillation counter, and others.

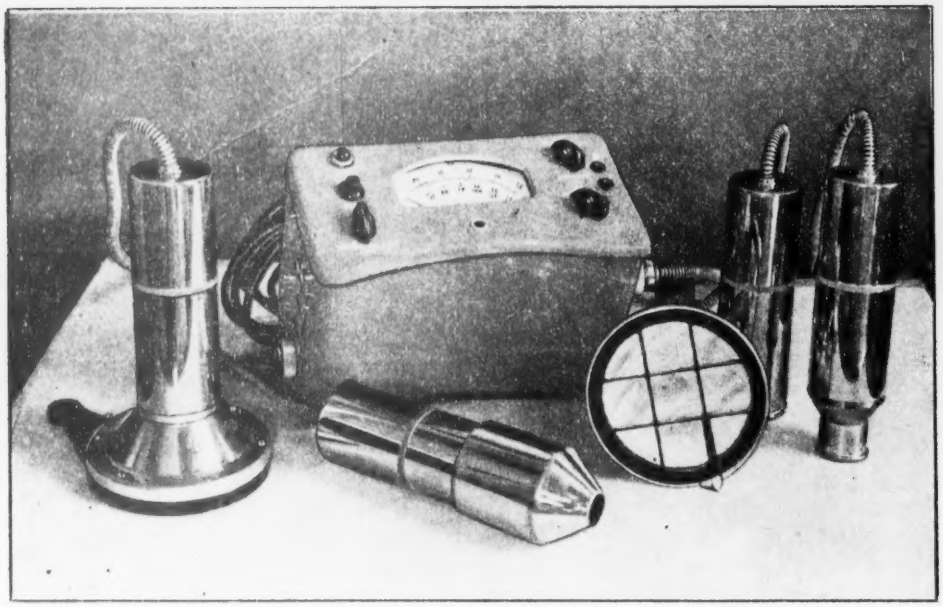


Fig. 2. The universal scintillation dosimeter.

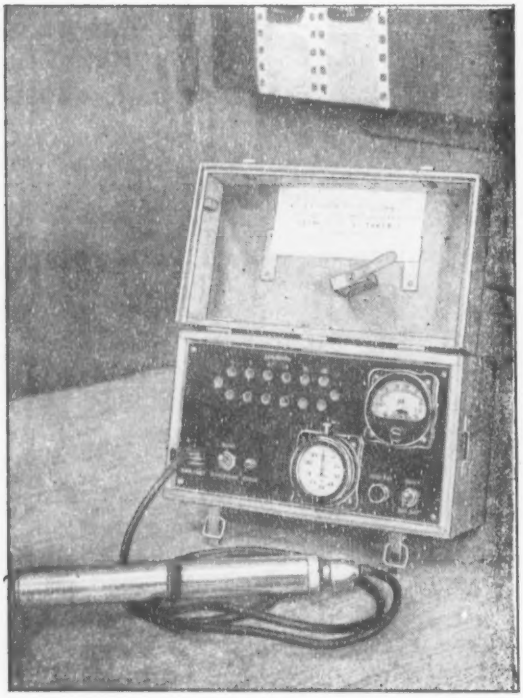


Fig. 3. IVP-64 meter for measuring the moisture content of soil.

Part of this section is devoted to the determination of the absolute age of rocks.

Tables of the main properties of materials used for reactor building are presented for the first time in the section "Materials for Nuclear Reactors."

Dosimetric instruments and shielding methods are extensively presented; many new instruments are exhibited, in particular, the individual dosimeter assembly ILK-1. The operation of the dosimeter is based on the use of tablets made from scintillating crystal phosphors as detectors, which have the property of storing energy when irradiated. The energy stored in the tablet is proportional to the radiation dose and is retained in the tablet for a sufficiently long period of time. When the tablets are further exposed to infrared rays the stored energy is emitted as visible radiation. The intensity of the flash from the phosphor depends on the radiation dose received by the tablet.

The following instruments are also demonstrated in the section:

– a portable electrofilter EF-2, which uses a-c power and is intended for collecting samples of air for determining the concentration of α- and β-active aerosols in the air. The collecting efficiency for aerosols is 85-95%. With the help of EF-2 it is possible to measure radioactive-aerosol concentrations up to 10^{-15} C/liter.

– universal scintillation dosimeter (Fig. 2) which is used for determining the radiation level in working areas.

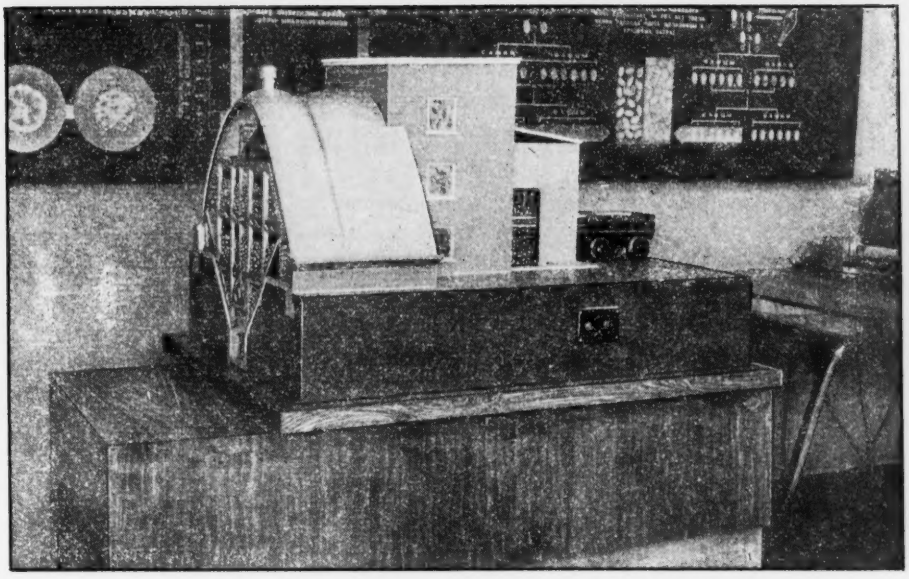


Fig. 4. Model of an experimental plant for irradiating potatoes.

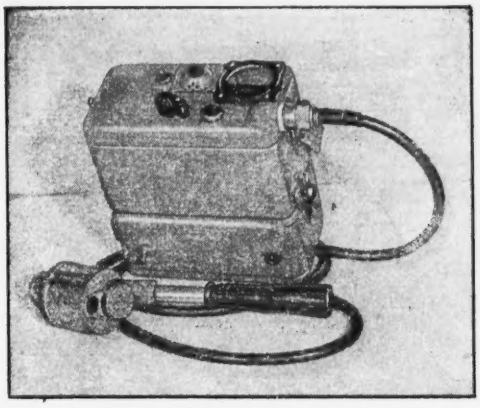


Fig. 5. Intensity meter for labeled atoms IMA-1.

The dosimeter registers radiation by means of a number of scintillation counters and a photomultiplier FEU-25;

– type RN-3 grid radiometer intended for the measurement of the fluxes of fast and thermal neutrons. The magnitude of the fast-neutron flux can be measured in the energy interval 0.5-14 Mev. Provision has been made in the instrument for signalling whenever the magnitude of the neutron flux exceeds each of two independently set levels and there is a pen for recording readings;

– portable radiometer RN-4 which has the same characteristics as RN-3 but is more compact;

– RAP-1 field alpha radiometer intended for the determination of the α-activity of samples of various substances under field conditions as well as in the laboratory. The instrument can also be used for determining the surface contamination of various objects by α-active substances. The range of measurement is between 50 and 100,000 disintegrations/min $\cdot$ cm^2.

Part of this section is devoted to the planning of radiological laboratories.

This year, two new sections have been created in the pavilion: "Science and Technology" and "Production of Isotopes." The section "Production of Isotopes" displays the methods used for obtaining radioactive and stable isotopes.

A big section is devoted to the application of radioisotopes and radiations in the national economy. This section has been enlarged for new instruments. Of these, the ones deserving most attention are: the IVP-64 meter for measuring the moisture content of soil (Fig. 3) and the radioactive gas-consumption meter RGR-1. IVP-64 is intended for the measurement of the moisture content of soil under field conditions, without extraction of samples and without a thermostatic drying. It can be used for the measurement of water storage in snow deposits during field surveys, the measurement of evaporation from the surface of the ground and also for work with

labeled atoms. The measurement of the moisture content of soil is based on the attenuation of γ-rays as they pass through the ground.

RGR-1 is a radioactive gas-consumption meter, intended for general industry, for the continuous remote measurement, recording and regulation of the consumption of various gases without interrupting the gas flow and without the introduction into the pipes of sensitive elements. The operating principle of RGR-1 is the compensation method for measuring the transport time of an ion packet produced in the gas by a periodic irradiation with the radioisotope Ru^{106}.

Here also is shown the work which was presented at the Moscow Conference on the Application of Radioisotopes and Radiations in the National Economy (April 1957); in particular, the work on the killing of mulberry silkworm chrysalises by γ-rays, performed at the Institute of Sericulture of the AN Georgian SSR.

Deserving notice is a model of the experimental plant for irradiating potatoes (Fig. 4), the equipment which can be used for studying the process of photosynthesis under natural conditions of plant growth and a large number of instruments used in radiobiology, for example, the intensity meter for labeled atoms, IMA-1 (Fig. 5), which works on both alternating current and batteries. Using IMA-1, β- and γ-radiation can be registered under field conditions or in the laboratory.

A separate section is devoted to the applications of radioisotopes and radiations in medicine. Equipment for γ-therapy, type GUT-Co 400, and a model of 25 Mev betatron equipment for medical purposes is presented here.

F. Musaev

THE FRENCH DUAL PURPOSE REACTORS G-2 AND G-3

As previously reported [1], the dual purpose reactors G-2 and G-3 will be erected in France. The distinguishing characteristic of these reactors is the construction of the shells, which, although designed to withstand internal pressure, are made of concrete. Recently [2-3], further data on these reactors were published, and are given in the accompanying table (see also Fig. 1 and Fig. 2).

Iu. K.

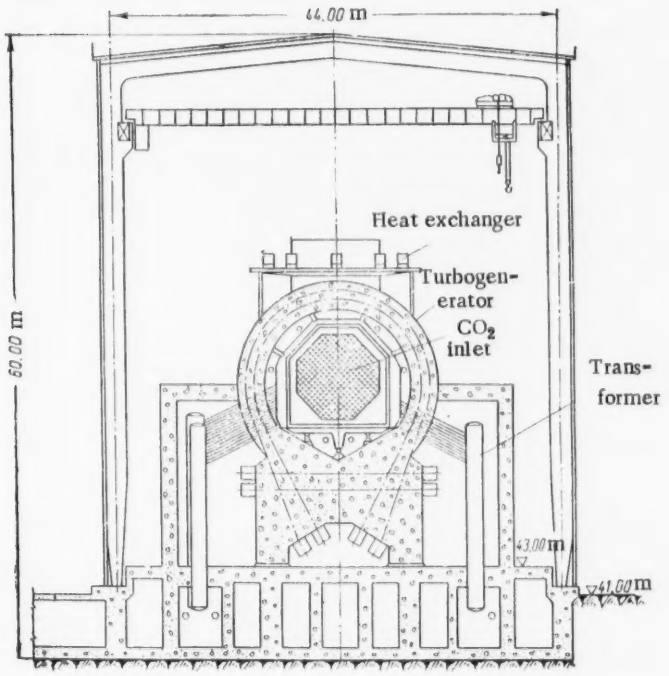


Fig. 1. Longitudinal cross section through the reactor building, G-2.

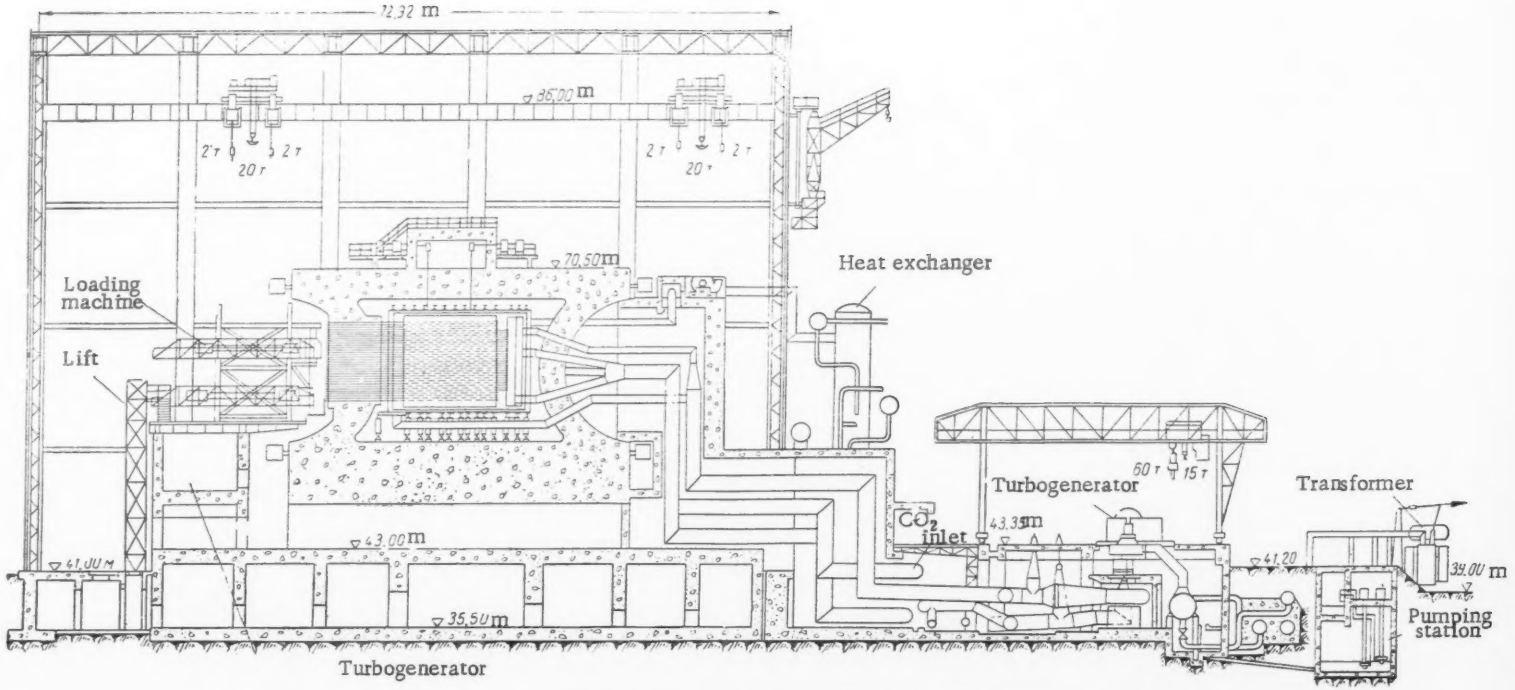


Fig. 2. Lateral cross section through the reactor building, G-2.

Characteristics of the Reactors G-2 and G-3

Storage and purification of CO_2	Reactor	Cooling system
1. Storage for liquid CO_2 (for both reactors) Total capacity – 90 tons Number of containing vessels – 3 Pressure – 20 atmos Temperature – 20°C 2. Vaporizer (for one reactor) Number of installations – 2 Installation output – 2 tons/hr 3. Gas storage (for one reactor) Total capacity – 11 tons Pressure – 22 atmos Number of containing vessels – 6 4. Purification is conducted continuously, parallel to the primary loop Mass flow through purifier – 1 kg/sec The purifier consists of: paper base filter activated charcoal for oil removal dryer, made of alumina	1. Fuel rods Fuel – natural uranium Fuel rod length – 30 cm Number of fuel rods per channel – 28 Number of ribs on each fuel rod – 16 Diameter of fuel rods located at the center of the reactor – 28 mm Diameter of fuel rods located at the periphery – 31 mm 2. Moderator Graphite – 1.7 g/cm^3 Cross section – 3.9 mbarns Length of graphite cylinder minus reflector region – 845 cm Diameter minus the reflector region – 785 cm Thickness of reflector region – 100 cm Grid – square Grid spacing – 20 cm Diameter of fuel channel – 7 cm Number of channels – 1200 Fuel channels are placed horizontally in the core Neutron flux at center of the reactor – $2.5 \cdot 10^{13}$ neutrons/cm^2·sec (at power level of 150 Mw) 3. Shielding (biological and structural) – pre-stressed concrete Dimensions: inside diameter – 1400 cm outside diameter – 2000 cm overall length – 3370 cm proof pressure – 30 atmos	1. Coolant Carbon dioxide Maximum operating pressure – 15 atmos Weight of CO_2 in the loop – 80 tons 2. Cooling of the core (primary loop) Number of zones: inlet – 2 outlet – 2 Temperature at inlet: central zone – 80°C outer zone – 150°C Temperature at outlet: central zone – 305°C outer zone – 354°C Flow (at 200 Mw) central zone: inlet – 528 kg/sec outlet – 821 kg/sec outer zone: inlet – 469 kg/sec outlet – 176 kg/sec 3. Main gas blowers Number – 3 (2 are held in reserve) Power consumption of the gas blowers – 2 × 3850 kw Drive – steam turbine, through a speed reducer – 1 × 2350 kw 4. Shield cooling (secondary loop) Flow at inlet – 540 kg/sec Flow at outlet – 500 kg/sec Temperature at inlet – 25°C Temperature at outlet – 50°C 5. Gas blowers in the secondary loop Number – 2 (1 in reserve) plus 1 in stock Power consumption – 2 × 670 kw plus 1 × 102 kw Drive – electric motor Maximum gas blower output – 500 kg/sec

Characteristics of the Reactors G-2 and G-3 (Continued)

Steam generation	Turbine	Generator and energy distribution
1. Heat exchangers Number – 4 (in parallel) Each installation includes: economizer intermediate pressure vaporizer intermediate pressure superheater high pressure superheater Steam parameters: high pressure steam: pressure – 10.7 atmos output – 47.76 kg/sec temperature – 334°C low pressure steam: pressure – 2.4 atmos output – 19.05 kg/sec temperature – 171°C 2. Boiler Water: flow at inlet – 48.6 kg/sec flow at outlet – 45.4 kg/sec inlet temperature – 115.5°C outlet temperature – 81°C Steam: output – 3.2 kg/sec pressure – 0.5 atmos 3. Distribution of generated steam High pressure steam to turbogenerator – 47.76 kg/sec Intermediate pressure steam to turbogenerator – 6.59 kg/sec Intermediate pressure steam to gas blower turbine – 12.46 kg/sec Low pressure steam to turbogenerator – 3.2 kg/sec	1. Turbine Shaft horsepower (three-stage) – 4 Mw Steam parameters: pressure, atmos: high pressure – 10.5 intermed. pressure – 2.2 low pressure – 0.5 flow, kg/sec: high pressure – 47.76 intermed. pressure – 6.59 low pressure – 3.2 temperature, °C: high pressure – 334 intermed. pressure – 171 low pressure – 81 2. Condenser Steam flow – 57.55 kg/sec Back pressure – 0.035 atmos Cooling water flow – 15,500 m^3/hr 3. Supplementary condenser Steam flow – 57.55 kg/sec Back pressure – 0.5 atmos Cooling water flow – 6590 m^3/hr Note: In the event of a turbine shutdown, the steam is fed directly to the condenser, and the reactor power does not change. In the event of a prolonged turbine shutdown, the steam is condensed in the supplementary condenser	1. Generator Nominal power – 45 mva Voltage – 10.5 kv Frequency – 50 cps Speed – 3000 rpm 2. Power section transformer Nominal power – 45 mva Primary winding voltage – 10.5 kv connection – delta Secondary winding voltage – 62 kv connection – Y 3. Supplementary transformer Nominal power – 6 mva Primary winding: voltage – 10.5 kv connection – delta Secondary winding voltage – 5.5 kv connection – Y 4. Energy distribution The transformer station for external distribution at 60 kv, of energy generated by the G-2 and G-3 reactors, is erected to the north of Marcoule

LITERATURE CITED

[1] J. Atomic Energy 3, 8, 173 (1957).*

[2] Engineering 184, 4771, 217 (1957).

[3] The British Nuclear Energy Conference 2, 3 (1957).

* Original Russian pagination. See C. B. translation.

AN ION-EXCHANGE METHOD FOR EXTRACTING PLUTONIUM FROM IRRADIATED URANIUM*

In Canada equipment is in operation for the extraction of plutonium from irradiated uranium through an ion-exchange method. Extraction is attained after the adsorption of plutonium from solution on a highly-basic anion-exchanging resin, which is resistant to radiation and chemically-active media. The plutonium is washed out of the column by a restoring solution of low acidity. The adsorption-desorption cycle is repeated twice to improve the purification of the plutonium.

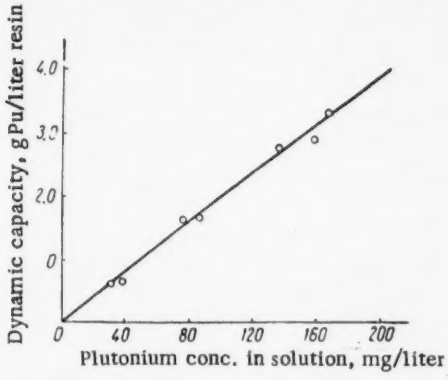


Fig. 1. Dynamic capacity as a function of plutonium concentration. Uranium concentration – 200 g/liter.

Let us consider the main stages of the ion-exchange process.

Adsorption of plutonium. The initial solution of uranium nitrate is fed to the column at the rate of 0.75-1.5 ml/min · cm^2; the maximum capacity of the resin with respect to plutonium is reached at an HNO_3 concentration of 7.5-8 N. This property does not change with increasing uranium content up to 1M. The variation of the dynamic capacity of the column with plutonium concentration, 200 g/liter of uranium being present, is illustrated in Fig. 1.

The amount of plutonium passing into the filtrate was between 0.5 and 1.2%. A large fraction of these losses was due to hexavalent plutonium, which is only slightly adsorbed with the acid concentration indicated. To decrease the loss, the addition of nitrous acid salts is recommended.

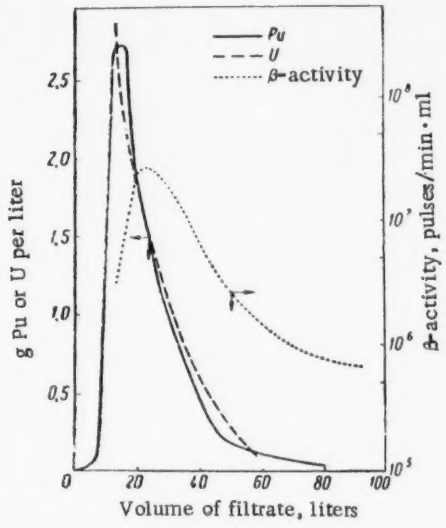


Fig. 2. Desorption of plutonium. Flow rate – 0.7 ml/min · cm^2.

Desorption of plutonium. As the desorbing agent a nitrate solution of hydroxylamine was chosen. From the elution curves (Fig. 2) it can be seen that 60 liters (volume of two columns) of 0.15 M solution of hydroxylamine desorbs practically all of the plutonium. Of the fission products mainly niobium is washed out, but more slowly than plutonium. During the recovery of the plutonium, the hydroxylamine yields gaseous products, but they do not have an adverse effect on the operation of the column. Nevertheless, the column was equipped with a device for degassing the adsorbent.

The second cycle. As the result of an analysis of the plutonium solution after desorption the following data were obtained:

* A. M. Aiken, Chem. Eng. Progr. 53, 2, 82F (1957).

Plutonium	1.0 g/liter
Uranium	1.5 g/liter
Coefficient of purification (according to β-activity)	$3 \cdot 10^3$

The filtrate contains a considerable quantity of uranium and active fission products; therefore, a further purification of the plutonium is necessary. The adsorption-desorption process is used for the second time. First of all, the solution of plutonium hydroxylamine was passed through a cation-exchanger (Dowex-50 and the plutonium was adsorbed as Pu^{III}; the losses were less than 0.1%. Then it was eluted with 7.5 N HNO_3 and was fed directly to the second column. The conditions for the sorption of plutonium during the second cycle were the same as during the first, with the exception of the considerably higher capacity of the resin for plutonium because of the low uranium concentration. The results of the analysis of the plutonium solution after purification are given below:

Uranium	0.015 g/g Pu
β-activity	2μC/g Pu
$(Zr-Nb)^{95}$	1.5μC/g Pu
Iron	0.003 g/g Pu
Coefficient of purification (according to uranium)	$2 \cdot 10^5$
Coefficient of purification (according to β-activity)	$5 \cdot 10^4$

The zirconium and niobium can be further removed using a column with silica gel as adsorbent. With this treatment, the γ-activity of the solution decreases by 10-20 times.

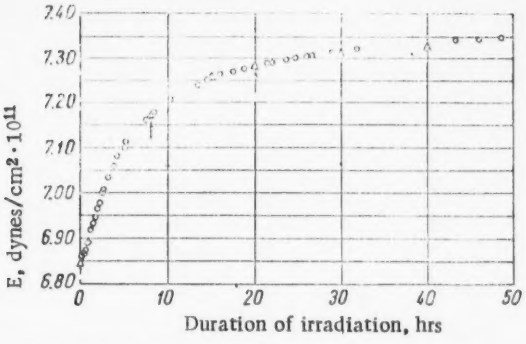
The results of the analysis show that the ion-exchange method does not give separation from the activity of the fission products. The γ-radiation of plutonium is very high and prevents the further processing of plutonium by the usual methods. Therefore, the method described can only be used together with an additional purification of plutonium, or with special methods for processing plutonium in the active form.

V. P.

RADIATION DAMAGE IN METALS AND SEMICONDUCTORS UNDER THE INFLUENCE OF γ-RAYS

Up to the present time radiation damage in semiconductors, and particularly in metals, has only been observed after irradiation by fast particles. It was recently shown [1, 2], that residual radiation changes can also occur after irradiation by hard γ-quanta.

In [1] the effect of γ-irradiation on the electrical resistance and the Hall coefficient of germanium, which were measured in the interval from liquid-nitrogen temperature to room temperature, was investigated. Irradiation of n-type germanium leads to a decrease of the number of carriers; after prolonged irradiation n-type germanium changes to p-type germanium. An investigation of the temperature dependence of the Hall coefficient showed that in n-type germanium two acceptor levels are formed: the first is 0.2 ev lower than the conduction band, the other – 0.26 ev above the edge of the valence zone. Irradiation of p-type germanium lowers the concentration of holes, but the rate of decrease of the number of carriers is considerably smaller than in n-type germanium. The change in the electrical properties of germanium after irradiation is due to the formation of defects.



The change of Young's modulus of a single crystal of copper [2] after irradiation by γ-rays from a Co^{60} source with an intensity of 900 Curies.

It was also established that an irradiation of a single crystal of copper during 50 hours [2] at room temperature by a flux of $4 \cdot 10^{10}$ cm^{-2} sec^{-1} γ-quanta with an energy of 1.2 Mev raises Young's modulus from $\sim 6.83 \cdot 10^{11}$ dynes/cm^2 to $\sim 7.348 \cdot 10^{11}$ dynes/cm^2.

The rate at which the modulus changes rapidly decreases as the exposure time is increased (see figure); therefore, irradiation for 50 hours leads to an almost complete saturation of the radiation damage. The increase of the Young's modulus under the action of γ-quanta is explained by the appearance of defects which clog the dislocations. The γ-quanta cannot directly lead to the production of defects since their interaction with nuclei is negligible. Equally unlikely is the formation of defects as the result of electronic or exciton excitation. Isolated defects (vacancies and interstitial atoms) can be formed through the action of Compton and photoelectrons produced by the hard γ-quanta. Calculations which take into account the cross sections of these processes give a number of defects which are, on the whole, in agreement with the experimental results. A comparison of these results with the results obtained for the irradiation of single crystals of copper by fast neutrons has enabled the quantitative estimation of the number of defects occurring per one fast neutron.

The investigation of radiation damage produced by γ-rays is of theoretical interest, since in this case point defects are formed at a great depth. Such defects are also formed in metals during irradiation by electrons with an energy higher than 1 Mev [3], but they are only produced in a thin surface layer (of the order of 0.1 mm) which the electrons can penetrate. On the other hand, the defects produced by the action of γ-quanta are distributed uniformly throughout the volume of a large sample; this enables the influence of the defects on the various physical properties to be evaluated and the nature of the radiation damage to be better understood.

Iu. S.

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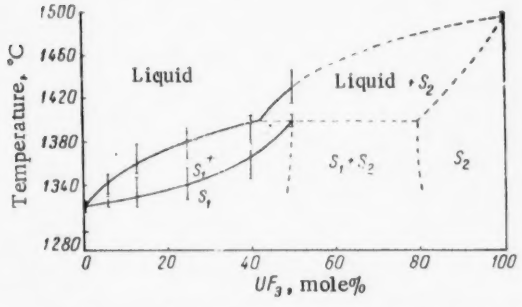
ON THE SYSTEM BaF_2–UF_3

A phase diagram of the system BaF_2–UF_3 (see figure) has been put forward on the basis of x-ray and thermal analyses [1]. Uranium trifluoride, containing < 2% UO_2, was obtained by heating stoichiometric quantities of UF_4 and uranium powder in an inert atmosphere. The mixed salts were melted in graphite crucibles in an atmosphere of argon purified by passing through a liquid-oxygen trap and over heated uranium chips. In order that the UF_3 should not disproportionate during melting [3] ($T_{m.p.}$ ~ 1495°C), the mixture of salts was heated rapidly to ~ 1480°C. Heating and cooling curves were taking in the range 1480-1510°C. During an hour's heating at 1500°C, UF_3 disproportionated ~ 20%; at 1300°C and below disproportionation was negligible.

Composition of salt mixture and color	Type of structure	Density, g/cm³		
		Calculated on the assumption of:		Measured
		Deficiency of anions or cations	Excess of anions or cations taken up	
75% BaF_2 + 25% UF_3, pinkish-brown	CaF_2	5.28	5.94	5.87
90% UF_3 + 10% BaF_2, intense violet-black	ZnF3	8.52	8.81	8.50



Phase diagram of the system BaF_2–UF_3. S_1 = solid solution of UF_3 in BaF_2; S_2 = solid solution of BaF_2 in UF_3.

An x-ray study showed that the lattice parameter of BaF_2 decreased from 6.189 ± 0.005 to 6.035 ± 0.005 kX when 50 mole % of UF_3 was dissolved in it. The parameters of the hexagonal lattice of UF_3 changed, on solution in it of ~ 20 mole % BaF_2, from a = 4.131 and c = = 7.335 kX to a = 4.197 and c = 7.359 kX.

From the data for the calculated and measured densities of the solid solutions of salts (see the table), it can be seen that during solution of UF_3 in BaF_2 fluoride anions take up $^1/_2$00 positions in the lattice, while during solution of BaF_2 in UF_3 atoms of uranium and barium are distributed at random on cation sites in the UF_3 lattice and part of the anion sites remain vacant.

G. Z.

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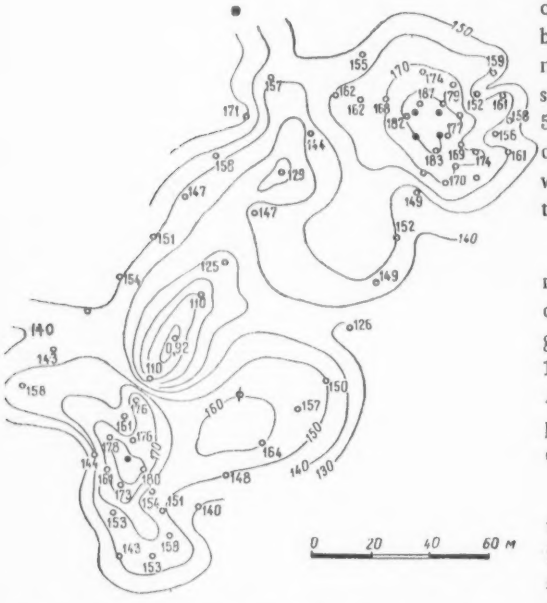
GEOTHERMAL METHODS OF PROSPECTING FOR URANIUM ORES

Because of the production of radioactive disintegration in uranium ores, heat is given off which accumulates in the surrounding rocks. One g of uranium in the course of a year gives off 0.71 cal. of heat [1]. According to Rankama [2], nearly 90% of the thermal energy obtained by radioactive disintegration is obtained from α-radiation.

Numerous investigations of temperature in drill holes and in mining operations which have uncovered uranium ores have shown that an increase of temperature is observed in the country rock near ore bodies. These data have served as a basis for the development of a method of prospecting for uranium ores by measuring the temperatures of rocks.

Investigatory work on the development of geothermal methods of exploration has been made on the broadest scale in the USA in recent years. For accomplishing these surveys a special highly sensitive apparatus was developed, registering temperatures with great precision [3].

A broad study of the temperatures in drill holes and mining operations on the Colorado Plateau was made. The principal ore-bearing formations of this region have been investigated – Morrison, Chinle, and Shinarump.



Locations of isotherms in an area of geothermal exploration of a uranium deposit on the Colorado Plateau according to Dennison. O) Drill holes 1.5 m deep; •) drill holes 18 m deep, intersecting uranium ore; ϕ) noneconomic uranium mineralization. The increase in the numbers on the isotherms, given in mv, corresponds to increased temperature.

These studies gave positive results, and in a series of cases led to the discovery of ore bodies which had been overlooked during earlier exploration. Thus in one mining operation in the White Canyon deposit in the state of Utah, a temperature anomaly was identified 55 m from the stope of one of the workings. Testing of the anomaly established the presence of an ore body with economic ore, which had not been intersected by the workings [3].

A series of investigations has permitted the planning of a definite method for geothermal measurement on the Colorado Plateau. At first the area to be investigated is covered by a network of shallow drill holes from 1.5 to 3.0 m deep in which the temperature is measured. After that the localities with the anomalous highest temperatures are explored with deep holes to delineate the ore body.

The results of one of these investigations are shown in the figure. In the area studied bore holes were drilled first to a depth of 1.5 m. As a result of temperature measurements two anomalies were discovered. A spread drilling of these anomalies uncovered two ore bodies at depths of 18 m. Succeeding tests have shown that in other parts of the area explored, where no anomalies appeared, ore bodies are absent [4].

Studies of several regions, having been explored by deep drill holes which passed through ore-bearing layers to their lower contacts, have shown that 50-70% of the

drilling operations might be economized by first using geothermal apparatus. For this, in Dennison's opinion [4], short holes should first be drilled over the entire area of the possible ore-bearing formation, and then, after measuring the temperatures in the short holes, continue only those drill holes which indicate temperature anomalies.

The geothermal method cannot contradict the radiometric, but in definite situations it may either replace it or be a fine complement to it, inasmuch as geothermal methods give clearer and more localized anomalies. Especially it might be used in detailed exploration and exploitation of small ore bodies not determinable by other methods.

During the study of geothermal exploration methods a series of technical difficulties have arisen connected with the influence of the temperatures of the surface, the penetration of the drill hole by water, and so forth. All these complications are being studied further and the method is being perfected. For the purpose of operation and installation, and also for developing the special apparatus in the USA, an organization, the "Geothermal Research Corporation," has been created.

It should be remarked that increased temperatures of rocks may be produced by other means than by radioactive ores. A significant emission of heat is observed with the oxidation of sulfate ores and organic substances. Temperature anomalies may be observed also at various tectonic ruptures and at other places. This makes possible the application of the geothermal method only in such geological conditions where other factors or raising the temperature will not disturb the clear delineation of the radioactive ore. In any case it should be applied only in regions where the geology is well known and in close association between the geothermal survey and geologic factors.

M. K.

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NEW ECONOMIC TYPES OF URANIUM ORE DEPOSITS

During recent years in various countries, chiefly in the USA, rather numerous uranium ore occurrences have been discovered in association with asphaltic substances in sandstones. All these had an insignificant uranium content and were small; therefore this type of ore deposit did not attract special attention.

In 1957 information was published on the results of exploration on the uranium deposit of Ambrosia Lake (state of New Mexico, USA), which is of the uraniferous, asphaltic-sandstone type. According to this information the Ambrosia Lake deposit is the largest, not only in the United States but in all of the capitalistic countries. This is confirmed by the following characteristics of the deposit.

The principal ore-bearing zone has been traced for almost 15 km with a width up to 1.5 km and an average thickness of the ore layer of 3.3 m (from 0.3 to 30 m). The average content of U_3O_8 is more than 0.30%. The total reserves of the deposit comprise 47 million tons of ore, i. e., 140 thousand tons of uranium oxide. The reserves of the Ambrosia Lake deposit constitute 72% of the uranium reserves of the USA.

The deposit was discovered in April, 1955. After half a year the total amount of exploratory drilling on it exceeded one million linear meters and nearly 5 million dollars had been spent on the work. At the present time more than 50,000 m of bore holes are being drilled each month [1].

For processing the ore of the Ambrosia Lake deposit, a mill is being built, one of the largest concentrating mills in the USA, to handle 3300 tons of ore per day. It will be located 40 km north of the Bluewater reservoir. Bsides this, it is proposed to build two additional mills with a total capacity of 2250 tons of ore per day [2].

The deposit is located in an area of an old oil field, having, as a consequence, the distinctive features inherent in oil regions. The ore-bearing localities are distributed in a domal structure. The ore zones are confined to the Westwater sandstone, which is a member of the Morrison formation. It is underlain by the Brushy Basin shales and overlain by the Recapture shales, also belonging to the Morrison formation.

The composition of the ore-bearing layers ranges from coarse-grained arkosic sandstone to pebble conglomerate. The cement is clay, calcite, or asphaltic substance. The asphalt here called black carbonaceous sediment is identical to humic acid. Its formation is associated with the process of migration of oil which first occupied the upper horizons of the domal structure, but after that, as a consequence of erosion and lowering of the water table, migrated downward along the beds.

The uranium is intimately associated with the asphaltic substance. It is represented by coffinite. The uraniferous asphaltic material surrounds and replaces grains of sandstone, especially the feldspar.

The ore deposit is restricted to a few horizons of the Westwater sandstone. The ore layers have irregular outlines. Occasionally several layers may be observed lying one above the other. In these cases their total thickness may exceed 20 m.

All the sandstone layers of the Westwater sandstone have a characteristic brick-red color because of the presence of hematite. The ore layers are discolored through the removal of hematite from the rocks by uranium-bearing solutions. Bleaching in the region is a characteristic prospecting indicator for uranium-bearing beds [3].

The formation of the ore deposit is the result of uranium, having been contained in relict waters of Morrison time, precipitating from these waters by the agency of the asphaltic substances [1]. Theories are also proposed that the uranium came in with descending waters which leached it out of the overlying rocks or that the uraniferous solutions are of hydrothermal origin [3].

The determination of the large-scale economic Ambrosia Lake deposit undoubtedly attracts the attention of uranium prospectors to this type of uranium mineralization. It also evokes considerable interest in oil-producing regions, inasmuch as similar geological conditions may be encountered there, leading to large-scale deposits of uranium ore.

M. K.

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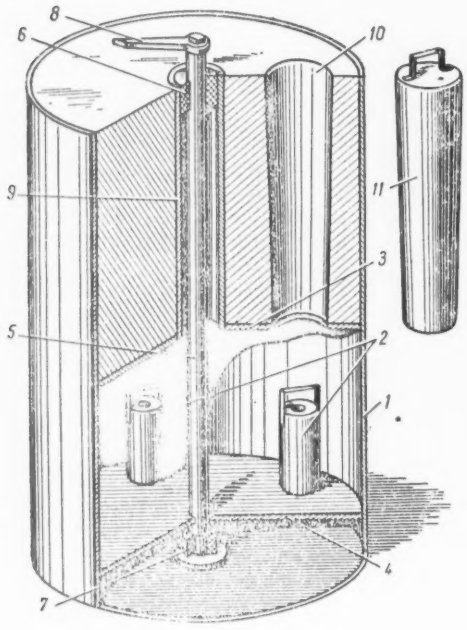
STORAGE TANK FOR γ-RADIATOR CONTAINERS

At the VNII for Hydraulics and Marine Development a very convenient storage tank has been developed for Type KV containers containing Co^{60} and Cs^{137} with a total activity of approximately 100 mg-equiv Ra.

The storage tank (see figure) is an iron tank 1 which is placed in the ground with a "carousel" device for containers 2. The cover, made from sheet iron 3, consists of two sections. The lower section, 40 cm high, is the storage space itself; the upper section, filled with concrete, serves as a shield against γ-radiation. The thickness of the concrete shield is 60 cm.



A storage tank with a carousel device.

The carousel arrangement consists of a rotatable platform 4 fixed to axis 5; the platform is made from sheet iron with strengthening ribs underneath, two bushings 6 and 7, and a handle-indicator 8 which serves for position-indication and rotation of the platform.

In the cover between sections and in the concrete there are central and peripheral holes. The guide shaft 9 and the bushing 6 are in the central hole. The peripheral hole 10, 15 cm in diameter, serves for introduction and withdrawal of the containers 2, which are placed on the rotatable platform at the periphery; this is done by rotating the platform about its axis using the handle-indicator. This hole is reinforced with sheet iron and is covered by concrete and the reinforced plug 11, which can be made in sections.

By making another hole in the upper section (close to the axis of the carousel device) it would be possible to place the containers in two concentric circles, thereby increasing the capacity of the storage tank.

The storage tank is provided with a hinged cover and hasps so that it can be closed and locked. Because the tank is set in the ground it must be water tight.

V. Emel'ianov

BRIEF COMMUNICATIONS

USSR. At the Laboratory for Cable-Transmission Line Construction of the Kiev division of the Central Scientific Research Institute for Communications, in 1956 there was developed a method for locating faults in the lead jackets of communication cables by means of radioactive materials; this method was put into actual use in 1957. Using a jet of compressed air, the radioactive gas is introduced into the cable in the region of the fault (the indicator gas can be radon or Br^{82} in the form of methyl bromide). In the cable the radioactive gas diffuses in the direction of the leak and penetrates into the ground at the fault in the jacket. Diffusing from a depth of 0.8-1.5 meters in 1-2 hours, the gas reaches the surface of the ground where it is detected by a field type γ-radiometer. The velocity of the gas in different types of cables is less than 1 km in 1-7 hours; hence the search for the point at which the tracer gas escapes is carried out on the day after the gas is introduced into the cable. The method has been used in working truck lines and is recommended as one of the most effective for swampy and frozen ground. To secure more efficient operation, a new γ-radiometer has been developed; this unit and the cable indicator use semiconductors. The device is small and light.

USSR. The Central Control Board on the Use of Atomic Energy, Council of Ministers, USSR and the Academy of Sciences of the Latvian SSR had an exhibition on the peaceful uses of atomic energy in Riga. More than 100 instruments and devices of many types were exhibited. Various types of measuring instruments, intended for the investigation of radiation were demonstrated. These included gas-discharge counters, ionization chambers and electromechanical impulse counters. Many of the devices were connected with industrial uses of radioactive isotopes. The work of the Institute of Physics of the Academy of Sciences of the Latvian SSR was also given wide coverage. Among the items shown were the following devices: thermal regulators, counters for counting objects on a conveyor belt, and an indicator for marking steel in a rolling mill.

Austria. The Central Control Borad on the Use of Atomic Energy Council of Ministries, USSR from October 18 to November 5, 1957 presented in Vienna an exhibit called "Atoms for Peace." The exhibit pointed up the use of atomic energy in various fields of industry, commerce, and science in the Soviet Union. Among the exhibits was a model of the first atomic power station in the world of the Academy of Sciences, USSR with a power of 5000 kw, a model of an atomic power station being constructed with a capacity of 420,000 kw and models and diagrams of various types of reactors. The Soviet film "Atomic Energy for Peaceful Purposes" was also shown at the exhibition.

England. At the Atomic Research Center at Harwell a stereoptic television device for manipulators has been put in operation. In contrast with the usual device of this type, this one contains two television cameras. At the screens two plane images of the same object are obtained – a left image and a right image. To obtain a three-dimensional representation special polarized filters are placed in front of the screen. One of the filters is polarized horizontally, the other is polarized vertically. In passing through the filters the two images are combined into one by means of a special mirror. The stereoptic effect is achieved when the combined image is viewed through appropriately polarized glasses. At the present time, the English scientists are working on the development of remote slave manipulators which will be provided with stereoptic television devices and will operate at distances up to 800 meters from the control panel.

England. An electrostatic accelerator of the tandem type with a proton energy of 12 Mev is being planned for Harwell and Aldermaston. The two stages of the accelerator are placed one above the other in a vertical plane. The potential of the central part of the tube is positive; the potential at the ends is zero. Negative hydrogen ions, extracted from a high-frequency discharge, are accelerated to an energy of 6 Mev in the first stage and then pass through a thin foil. The protons which are formed in this process as a result of "charge exchange" double their energy in the second stage of the accelerator. Because of the difficulties involved in obtaining

negative hydrogen ions the beam current of an accelerator of this type is smaller than that of a one-stage Van de Graaff accelerator. The high pressure chamber is 2.7 m in diameter and 13.5 m in height. The gas pressure is 17.5 atmos and the weight of the gas is approximately 2 tons.

England. Financial approval has been received for the construction of a 7-Bev proton synchrotron. The cost of the accelerator is estimated at about 7,000,000 pounds sterling. The synchrotron will be constructed at the airfield at Harwell and will be the main machine for carrying out research at the National Institute for Research in Nuclear Problems.

England. The General Electric Company has developed a 3-dimensional, closed-circuit, color television system for operation with reactors used in the development of an atomic engine for aircraft. The system makes it possible to monitor the lattice points of the reactor and to obtain an accurate idea of the depth in those stages in which this information is necessary for proper operation of the reactor points.

USA. The army portable power reactor APPR-1 has been operated at Port Belvoir for 700 hours. During this time the total outage time of the reactor (for control and maintenance) was eight hours. During more than 600 hours the unit generated electrical power at a level higher than the design capacity of the apparatus. During the entire time of operation a total of 1,181,000 kw-hr of electrical energy was generated.

England. An experimental thermonuclear zero-power reactor (Zeta-1) has been built; as expected, this apparatus makes it possible to achieve temperatures at which fusion of hydrogen nuclei can occur. The apparatus will be operated at temperatures of the order of 100,000,000°C. The apparatus was built by the Metropolitan-Vickers Electrical Company.

England. On the tenth of October, 1957, a serious accident occurred at one of the two reactors used for generating plutonium at Windscale; the accident was caused by unanticipated heating of the uranium slugs located in the core of the reactor which had been shut down for periodic recharging of the fuel. The cause for the overheating of the fuel was not given. To reduce the temperature of the fuel in the reactor, it was flooded with water.

The overheating of the fuel destroyed the anti-corrosion covering of a number of uranium lumps; as a result a considerable amount of radioactive material was exhausted by the cooling system of the reactor to the outside (the Windscale reactors are cooled by an open-circuit air-cooling system). An area 3 km wide and 12 km long around the reactor was contaminated by radioactive materials.

The reactor at which the accident occurred is one of the largest English reactors and has been in use for seven years. Because of the accident it will be out of service for several months.

Hungary. In accordance with a decision of the Council of Ministers of the Hungarian National Republic, the Atomic Energy Committee was reorganized in November 1957. One of the tasks which will be undertaken by the reorganized committee will be to appraise the potential uses of atomic energy in the country; to plan for further development on the basis of this estimate.

German Democratic Republic. In Rosnidorf (near Dresden) work has been completed on the construction of a water-cooled research reactor. The capacity of the reactor is 2 megawatts. Enriched uranium will be used.

Greece. The Greek government has decided to form an Atomic Energy Agency. This agency will be responsible for the construction of reactors for research purposes.

Egypt. At the VOKS exhibition in Cairo in September-October, 1957, there was a Soviet exhibition on the "Peaceful Uses of Atomic Energy." The Soviet scientist O. I. Kozenets presented a lecture on the "Peaceful Use of Atomic Energy;" a Soviet film on the same subject was also shown.

Egypt. The Secretary of the Egyptian Atomic Energy Commission, Ibragim Abdul Rahman, has announced that Egypt will build an atomic power station during 1962-1967. He also announced that a reactor imported from the Soviet Union will be put into operation in the beginning of 1958 and added that at present 150 Egyptians are receiving training in the field of atomic energy.

India. The total uranium deposits in India are estimated as lying between 12 and 14,000 tons. Of these 6-7000 tons are concentrated in monazite sands with a uranium content of from 0.2 to 0.46%; 3-4000 tons are in ores in the region of Snigkhboom where the U_3O_8 content is 0.03-0.1% and up to 3000 tons are in ores in the Aravalli chain.

Italy. The Italian government and the International Bank have concluded an agreement relating to the organization of scientific research work on the construction of an atomic power station with a capacity of 150 megawatts in southern Italy.

Italy. At the end of June 1957, in Rome there was an international congress on Nuclear Physics and Electronics. Present at the Congress were scientists from Italy, USSR, USA, England, France and other countries.

At the plenary sessions and sections of the Congress information was presented on the design and construction of nuclear reactors for electric power stations, problems of automation for industrial processes, the organization of various types of communication, construction of complicated electric devices, etc. In particular, the Italian Marconi company aroused interest with an interesting demonstration of devices using visible light and infrared rays.

The Soviet delegation presented reports on "Electronoptical Device for Observation of γ-Rays" (P. V. Timofeev), "Counters for Nuclear Research" (A. A. Markov), "The Electronic System of the Proton Synchrotron at the Joint Institute for Nuclear Research" (A. A. Vasil'ev).

Kerrer (USA) presented a report on the startup of a new experimental atomic power station with a boiling-water reactor EBWR. The report indicated that a rather high activity is observed in the vapor in the condenser of the turbine (approximately 4000 μr/hr).

Martinoli (Italy) reported on plans for the use of atomic energy in Italy and presented data on atomic electric power stations in that country. Construction will be started in 1957 in Italy on atomic electric power stations (water-water and graphite reactors); the following power schedule is anticipated: 320 megawatts in 1962, 1950 megawatts in 1965 and 12,000 megawatts in 1975.

In a report presented by Amaldi (Italy) it was announced that in the near future in Italy a center will be set up for physics research in the high-energy region. In 1958 a research reactor will be built. A Van de Graaff generator with a capacity of several million electron volts is finished. A 30-Mev betatron is in operation. In the near future a 1-Bev synchrotron will be started up in Frascatti; this machine was designed in Italy and built by Italian industrial firms. In addition, Italy will use for research purposes the 700-Mev accelerator and the 25-Bev accelerator at Euratom. At the present time, in Italy there are about 300 workers in the field of nuclear physics. To train personnel needed for the development of atomic energy about 7500 specialists will be trained.

Canada. In September work was started on the largest mine in the world for extraction of uranium (Consolidated Denison) near Lake Elliott (Province of Ontario). This is the fourth mine at the Blind River deposit, which was discovered four years ago. At the deposit there are six mines under construction which have not been added to the system. All these mines will, in the next five years, yield to the government agence "Eldorado Mining" uranium oxides worth more than 1,061 million dollars. In the middle of August "Consolidated Denison" processed 2600 tons of ore per day and at the end of November was processing 6000 tons. Its total capacity is 10,000 tons.

Pakistan. In the region of Khazar in the Province of Punjab a uranium deposit with high quality ore has been discovered.

Syria. An International Fair, in which the Soviet Union participated, was held in Damascus from September 1 to 30, 1957. The Soviet pavilion was visited by more than a million people during the fair. The section of most interest in the pavilion was that devoted to the "Peaceful Uses of Atomic Energy." The visitors' book contained numerous entries by visitors not only from Syria, but also from Lebanon, Iraq, Jordan and other countries.

USA. According to the 22nd Semi-Annual Report of the Atomic Energy Commision, USA, the production of oxides and lower oxides in the uranium concentrators at 12 operating refining plants during the first half of 1957 was 3810 tons as compared with 3084 tons in the second half of 1956. The total output of these plants is 9210 tons of ore per day. When ten new plants, which are in the design or construction stage, are put into operation the total capacity of plants engaged in refining ore will reach 18,305 tons per day.

USA. The General Electric Company has constructed for the AEC a periscope 27 m long made from aluminum. The periscope will be set up at the National Reactor Testing Stations close to Idaho Falls. It will serve as a special "eye" required for development for reactors for use in airplanes. A system of mirrors and lenses makes it possible for an engineer behind a heavy shield to observe the operation of the nuclear reactor.

USA. The Alco Products Company has designed an experimental high-temperature reactor using a helium coolant having a capacity of 50 megawatts. The core of the reactor consists of a number of parallel tubes filled by graphite pellets containing uranium. It is proposed to obtain steam at a pressure of 101.5 atoms and a temperature of 537 °C from this reactor.

USA. A 10-Mev electrostatic accelerator of the tandem type is to be installed shortly at the University of Florida. Both stages of the accelerator are positioned horizontally. The entire apparatus will be located in a high-pressure steel tank 2.4 m in diameter and 10.2 m long. The total weight of the accelerator will be 35 tons.

USA. A group of scientists at the University of California Radiation Laboratory (Berkeley) have discovered the 13th isotope of plutonium – Pu^{233}.

USA. The Pacific Nuclear Electronics Corp. has developed a 100-channel pulse height analyzer. The pulse heights are determined by a time transformation method which uses an oscillator stabilized by a quartz crystal. The memory elements are magnetic cores. The capacity of the analyzer is one million pulses per channel. The linearity is 0.2%. The counting loss which arises as a result of the appearance of the pulse while the preceding pulse is being analyzed is kept to a minimum by storing the last-received pulse while the preceding pulse is being analyzed. The results of the measurements are printed out on a tape.

USA. The design of a proton synchrotron (synchrophaseatron) with weak focusing and an energy of 12.5 Bev is under way at Argonne National Laboratory. The dimensions and cost of the magnet will be considerably reduced since the intensity of the magnetic field has been chosen at about 50% higher than in other accelerators of similar type. The proton yield is expected to be an order of magnitude larger than in any presently available accelerator in this energy range.

USA. On June 21, 1957 construction was started on the first continuous school for nuclear energetics for the Navy Maritime fleet. The school will be located at the submarine base in Groton, Connecticut.

France. In Saclay work has been started with a heavy water research reactor EL-3 which was built in the United States. The reactor reached criticality on July 9, 1957.

France. An accident occurred at one of the gas-cooled reactors in Marcoule. The temperature of the fuel rods increased rapidly, causing the magnesium coating of the rod to burn so that the uranium started to melt. The molten uranium penetrated the graphite and obstructed the reactor stack. The reactor was withdrawn from service for three months. The cause of the accident is not known.

Federal Republic of Germany. Processing of uranium from an ore deposit located in Fichtenberg, near Weissenstadt has begun. The deposit of uranium ore is estimated at 80-100,000 tons. The ore at this deposit is of medium value as far as uranium content. The plant for processing uranium concentrates in Weissenstadt will extract 10 tons of U^{233} per year in the second half of 1958, with 0.7% U^{235}.

Federal Republic of Germany. Western Germany has given the English company Kidd-Wrightson an order for the construction of a nuclear reactor for delivery in 1959. This reactor will cost one million pounds of sterling and will be turned over to four West German universities (TASS).

Czechoslovakia. On September 25, 1957, in Gusintse-Rzhezhi, near Prague, the first nuclear reactor built in Czechoslovakia was started; the installation for the reactor was provided by the Soviet Union. Soviet specialists also helped Czechoslovakian technicians and builders in the assembly of the reactor. The Czechoslovakian reactor has a capacity of 2000 kilowatts. The reactor will be used to produce isotopes for a number of scientific investigations and for practical application. At the present time construction is being carried out on a cyclotron and a number of other units at the Institute of Nuclear Physics of the Czechoslovakian Academy of Sciences.

Switzerland. Operation of a 600-Mev phaseotron (synchrocyclotron) for protons has been started at the European Center for Nuclear Research (CERN).

Japan. A high-quality uranium ore deposit has been found in the southeastern part of Ywate. It is located in a mountainous region at a height of about 500 meters above sea level. The deposit is called the Onigazava deposit.

Japan. The chairman of the Japanese Atomic Energy Commission, Koitsa Uda, has returned to Japan after a journey in Great Britain and the United States. He declared that the purchase of an English power reactor of the Calder Hall type will be more practical than the purchase of an American type PWR reactor. The cost of construction of an electric power station of the Calder Hall type is about 30% cheaper in Japan than in England; in the future it would seem that the cost of electricity can be brought to less than 4 yen per kilowatt-hour. The reactor can be started up within four years after the order is placed. A reactor of the PWR type can be put into operation in a shorter time; however, as was indicated, for Japan it would be more practical to import a reactor of the Calder Hall type. According to Uda, England is prepared to furnish Japan with a considerable amount of uranium.

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BOOK REVIEW:

AN INADEQUATE BOOK TRANSLATION

The State All-Union Shipbuilding Industry Press at Leningrad has published a Russian translation of a book by S. McLane, a scientist at Argonne National Laboratory (USA), called Lectures on Reactor Design.* This book is based on a series of lectures given by the author in 1953-1954.

Soviet scientists have at their disposal a number of translated works concerned with various problems of nuclear engineering which are covered with varying degrees of thoroughness. All these works complement each other and the book being reviewed here may well be added to their number since it is devoted to problems of practical interest. However, for reasons which will be discussed below, the Russian translation of this book cannot be considered adequate.

As indicated by the author, the purpose of the lectures is primarily to acquaint the reader with the basic problems of reactor engineering rather than to describe all the factors which enter into this subject.

The book contains 28 lectures. These cover the construction principles in various existing nuclear reactors, the physical problems involved in reactors and reactor control, the problems of choice and utilization of reactor materials, the effects of radiation and the nature of radiation damage, the technology involved in the manufacture of nuclear fuel, radiation shielding, heat transfer, operation of nuclear reactors, cost factors and so on.

All these problems are covered thoroughly by the author and there is an abundance of illustrative material (tables, graphs, sketches, diagrams, etc.).

In the lectures which are devoted to mathematical analyses of various problems there are practical examples of calculations which help in understanding the material in the book. Actually, the presentation of the lectures is not systematic: a given lecture is unrelated to the one which precedes it; nevertheless, the lectures can be divided into broad categories. However, this shortcoming in the American edition is not important. With competent translation and editing, the book should be useful both for specialists and those interested in problems of reactor engineering.

A basic shortcoming of the Russian edition of the book is the extreme carelessness and, in a number of cases,poor scientific editing, with which it was prepared.

It is well known that a translation from a foreign language should not be literal; rather, one should be concerned with equivalent meaning and technical and stylistic literacy. It is precisely in this respect in which the book being reviewed is deficient; there are a number of errors of technical nature: a number of statements and conclusions cannot possibly be understood since they are extremely complicated and distorted. Established terminology is frequently completely ignored in the book and use is made of new and poorly understood terms. In certain cases the English terms are simply transliterated into Russian although there are well-established equivalent Russian expressions and terms.

Here are several examples.

On page 103 we have: "We consider a reactor of cubic shape, with sinusoidal heat generation in three directions x, y, z with zero on the surface and without a reflector." It is not clear what is meant by the expression "zero on the surface of the reactor;" in the English original, however, it is clearly indicated that the heat generation at the surface of the reactor is zero. On page 153 we encounter the following expression: "Reac-

* S. McLane, Lectures on Reactor Design (Sudpromigiz, Leningrad, 1957).

tors with light water are susceptible in very short periods, approximately 10^{-3} sec, to a rapid minimum critical limit." It is impossible to understand this phrase although the original indicates that light-water reactors exhibit very short periods and that, consequently, the time required to achieve momentary criticality is a minimum. These examples, which distort the problems being considered, can be extended almost indefinitely.

A serious shortcoming of the Russian edition of the book is the large number of extremely careless and slovenly constructions. Some examples follow: "Ten thousand curies of radioactivity were directed into the cellar" (page 53), "The rods tend to destroy the neutron flux" (page 54), "The rods are loaded with springs" (page 56), "All ideas . . . are incorporated in reactors with hard metal fuel" (page 53), "Heat will flow from slab to slab and depend on the temperature of both slabs" (page 107), "The tests were carried out on the MTR at a power of 5 megawatts in order to obtain sufficiently small values of contamination, which the reactor could overcome" (page 71), "The sodium flows through the pump in the thin-walled tube" (page 163), etc.

The terminology used in the Russian edition of the book also leaves something to be desired. As has been already noted, for some reasons use is not made of widely known and established terminology. Thus, for example, the rods used for fine control of the reactor in some cases are called "shim rods" (page 153), in other cases (page 151) "rod-shims" (whence the terms "shimming," page 152); in place of the term "poisoning of the reactor" the term "contamination of the reactor" is used (page 147); the energy yield for a ton of fuel is called "radiation" (page 149), while the pattern of heat generation along the height of the reactor is called a "section of the upper roof" (page 152); the absorbing material of the rods is called "a poisoner" (page 152); reactors with positive and negative reactivity temperature coefficients are called, respectively, "self-catalyzing" and "nonself-catalyzing" (page 171), while the attenuation of radiation is called "the reduction of the level" of radiation (page 117). There are numerous examples of this kind.

Finally, we must comment on the introduction to the translation of the book written by A. A. Kanaev. This paper contains a list of all existing reactors and those being designed or constructed in the USSR or abroad; however, this list is presented without a systematic or logical explanation for the choices of the various types of construction which were used. The paper contains a large number of figures and data but the presentation is not very clear. There are serious errors. For example, it is maintained on page 9 that in the first Soviet atomic power station the "excess power can be reduced by 18 compensating rods" although, as is well known, the control rods absorb excess reactivity and not power. Hence, we cannot agree with the publisher that the introductory article supplements the book and facilitates its reading by the student who is not already familiar with the basic problems of atomic energy, and, in particular, the prospective application of nuclear engines in ship design.

In conclusion, we must note that the book being reviewed here cannot on the whole, be considered a satisfactory work.

V. N. Artamkin

NEW LITERATURE

Books and Collections*

Problems of nuclear engineering. Collection of translations and reviews of foreign periodical literature No. 3, Izd. IL (1957) 100 pp, 7 rubles.

The section "Power Stations and Plants" contains translations of papers on the English Calder Hall atomic power station appearing in Nucl. Engng. 1, 7 (1956), "Agreements for the construction of atomic power stations" from Engng. and Boiler House Rev. No. 1 (1957), "A comparison of the construction of industrial atomic power stations" from Nucl. Engng. 2, 10 (1957), "Operating experience with the power plant BORAX" from Nucl. Sci. and Engng. 1, 5 (1957), "Self-regulating direct-flow boiling-water reactor" from Nucleonics 14, 7 (1956), "The switching on of the PWR" from Nucleonics 14, 7 (1956).

The section "Constructions and Materials" contains a translation of the paper "The construction and operation of refrigerated packing for valves and pumps" from Chem. Engng. Progress 52, 4 (1956).

The section "Shielding" contains a translation of the paper "The problem of eliminating liquid and gaseous waste at Windscale" from J. Brit. Nucl. Energy Conf. 2, 1 (1957).

The section "Reference Materials" contains the continuation of the table of reactors according to the country of location (reactors being constructed or planned) taken from Atomwirtschaft No. 10 (1956) (the beginning of the table was published in collection No. 1).

The section "News of Nuclear Engineering" contains a translation of the paper "A detached steam superheater" from Heat Engng. 31, 5 (1956), a translation of the paper "A preliminary study of boiling-water reactors with superheated steam" from Nucl. Sci. and Engng. 1, 2 (1956) and brief reports from 203, 5267 (1957).

Atomic Technology Abroad. Monthly collection of translated material (No. 2, October 1957, Atom Press, 83 pp, 5 rubles). The collection begins with the review "Reactor building in England" compiled from materials published in the third annual report of the United Kingdom Atomic Energy Authority and in English journals. The article "Demonstration nuclear power plants in the USA" is a review compiled from the papers presented at the annual Pan American Conference of the Institute of Mechanical Engineers, held in November 1956, which were published in the journal Mech. Engng. 79, 3 (1957). The collection contains translations of the papers "The planning and construction of reactors for engineering tests" (275 Mw power) and "Uranium regeneration at the Oak Ridge gas-diffusion plant," presented at the second Conference on Science and Technology in March 1957 in Philadelphia, USA. There appear translations of the papers "The application of radioisotopes to industrial research and to the control of industrial processes" from J. Roy. Inst. Chem. 80, 694 (1956) and "Catalytic fusion of light nuclei in the presence of μ-mesons" from Phys. Blät. 13, 4 (1957).

The section "News" presents brief items "Some questions of the economics of atomic power engineering," "Prototype aviation reactor," and "The construction of tandem accelerators in England."

Brief reports give the latest information on work abroad in the field of atomic energy.

Nucleonics No. 9, 1957. Some aspects of the development of atomic technology are summed up in this issue and an attempt is made to evaluate the problems facing this branch of technology.

The article "Power reactors," consisting of five independent sections written by different authors, occupies a large part of the journal.

* Titles of papers cited in these collections have been translated from the Russian, but have not been verified against the original English publications. Some discrepancy of wording may therefore occur – Publisher.

The first section (W. Davis, L. Roddis and C. Goodman) is devoted to a description of the various problems which faced the USA Atomic Energy Commission in the last few years, as well as of the problems which have to be solved in the near future. These problems are chiefly connected with the development of atomic power engineering in the USA. In the second section (author C. Starr) the economics of nuclear engineering are discussed and a review is given of the technical trends which improve the economic index of the atomic power stations. The third section (author W. Zinn) deals with the problem of constructing power reactors in the next 10 years (increasing the coolant temperature, using natural uranium, the specific power of various reactors and a number of other questions). In the fourth section (author P. Sporn) the commercial aspects of nuclear engineering are examined, the economic expediency for constructing atomic electric power stations is evaluated and the question of economics is considered. Finally, in the fifth section (author A. Iddles) the production of reactor materials is discussed and the question of satisfying the demand for them in the next 10 years is considered.

The next article (author D. Taylor) is devoted to the use of various nuclear instruments in nuclear technology.

Next, in R. Goodwin's article the problems associated with the use of atomic energy for ship propulsion is discussed and the future trend of atomic ship building is evaluated. A comparison of atomic ships having reactors of different types is made.

W. Libby's article deals with the use of radioisotopes. The author suggests that, since the methods used in radioisotope application in different branches of industry are similar, in the next 10 years the organization for the control and supervision of radioisotopes will become standardized. In the next 5-10 years the demand for Co^{60} sources will be greater than 10 million curies per year.

G. Scharf-Goldhaber's article gives a condensed account of the progress and present position of nuclear physics.

In C. Coryel's article it is pointed out that the clarification of the fission-process chemistry requires an increased effort in experimental chemical research in this field. The author also discusses several published investigations devoted to the analysis of fission problems.

A very brief review of the problem of controlled thermonuclear reactions and of the experimental work published within the last five years in this field is given in the article by A. Bishop.

A review article by B. Spinrad is devoted to questions of reactor physics. This article points out the growing role of calculating machines in the solution of problems occurring in reactor-design work and particularly in the mocking up of kinetic processes of a nuclear reactor. The author emphasizes the role of reactor physicists in creating thermonuclear reactors.

R. McCullough's article deals with the question of reactor safety. In the article, the problem of the health of personnel operating nuclear reactors is considered. The necessity for more detailed calculation and investigation of critical systems is emphasized, inasmuch as an exact knowledge of the peculiarities of their behavior will ensure safe operation.

In his article, D. Leeser attempts to predict the trends for the creation of reactor materials that are stable to the influence of radiation. He points out that within the next 10 years the phenomenon of ductility will be understood and a lower limit will be specified. He surmises that in the near future it will be necessary to produce materials capable of operation at temperatures of 1700-1800°C.

In S. Lawroski's paper it is reported that by 1960, in existing solvent-extraction plants for reprocessing nuclear fuels, a large part of UF_4 will be obtained by a continuous process. There is hope that the pyrometallurgical reprocessing of nuclear fuel will be mastered and will compete economically with solvent extraction.

It must be remarked that, on the whole, the contents of the September 1957 issue of the journal Nucleonics are of a descriptive nature.

To a large extent the contents deal with the problems facing nuclear physics and technology. A large proportion of the information is not new.

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CONFERENCE OF READERS OF THE JOURNAL

In September 1957, in Moscow, at the F. E. Dzerzhinskii House for Scientific and Technical Propaganda the first conference of readers of the Journal of Atomic Energy was held.

A. V. Lebedinskii, Corresponding Member of the USSR Academy of Medical Sciences, was chairman at the Conference. Academician A. I. Alikhanov gave a brief introductory talk in which he welcomed the readers on behalf of the USSR Academy of Sciences.

A group of readers of the journal – conference participants (left to right): B. A. Semenov, Lenin Prize laureate A. K. Krasin, V. N. Artamkin, I. L. Chikhladze.

Photograph: I. Akulenko

The report of the Chief Editor, Professor I. I. Novikov, titled "The journal and its readers" was read by the secretary of the editorial office B. V. Semenov. The report stated that with every year the problems of atomic science and technology are more extensively presented in general, scientific and technical, nonspecialized journals and newspapers, with every year the number of specialized "atomic" journals, monographs, pamphlets increases. At the present time all over the world about 30 journals appear devoted to the problems of atomic energy.

In the Soviet Union the Journal of Atomic Energy is the only publication of this type. This is explained by the fact that, in addition to original and review papers, the journal publishes a variety of scientific and technical information and has a section "Criticism and Bibliography." The journal is aimed both at the specialists in the field of the production and use of atomic energy and at a wide circle of readers interested in these problems. Its first issue appeared in April 1956.

At the present time the journal is circulated in all of the districts, regions and republics of the Soviet Union; readers of about 30 other countries are subscribers. In addition, in five countries – China, USA, England, GDR and Japan – the journal is republished in Chinese, English, German and Japanese. Separate supplements to the journal are also reissued in other countries. Further, foreign journals publish translations of some articles.

The report gave a detailed review of readers' letters and comments about the journal.

In the concluding section of the report editorial plans for the future were announced and it was pointed out that the Journal of Atomic Energy will lay stress on applied and engineering problems.

In the report it was pointed out that the 16th Printing Office, where the journal is printed, is very careful in its production at a high technical level and shows initiative in keeping to the publishing schedule.

All of the speakers at the readers's conference remarked that the journal has performed a big task in presenting the most important problems of atomic science and technology and wished the editorial office further success. At the same time, critical remarks were also expressed.

A reader, V. N. Artamkin, said that the publication time was too long, not all problems that interest readers are presented in the journal. These are, for example, the mocking up of processes occurring in nuclear reactors, the use of computing machines in the design of nuclear reactors, etc.

N. E. Kukarkin would like to see more material on nuclear technology, atomic power engineering and electron physics.

P. B. Pribytkov's opinion is that many important problems of interest to geologists are completely neglected by the journal.

G. M.Kukavadze expressed a wish for a change of the journal's cover and reported that the journal takes a long time to reach remote areas. Thus, in Tbilisi at the beginning of September the July issue had not yet been received.

B. G. Dubovskii pointed out the unnecessary complications in the submission procedures for the journal and proposed that a list of unpublished material be published in the journal.

A reader, A. N. Solov'ev, considers that in view of the abundance of material to consider the question of producing new "atomic" journals in the country.

A. M. Bekarevich, a reader, devoted his talk to the problem of safety techniques. He wished that the journal would help attract specialists to organize teaching facilities in universities and technical colleges for safety techniques for industries employing atomic energy.

An exhibition was organized in the foyer on "Literature on the Peaceful Uses of Atomic Energy."

After the conclusion of the conference its participants saw the popular science film "Atomic Energy for Peaceful Purposes."

A record of the conference proceeding will be sent on inquiry to interested individuals and organizations.

V. Petrov

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